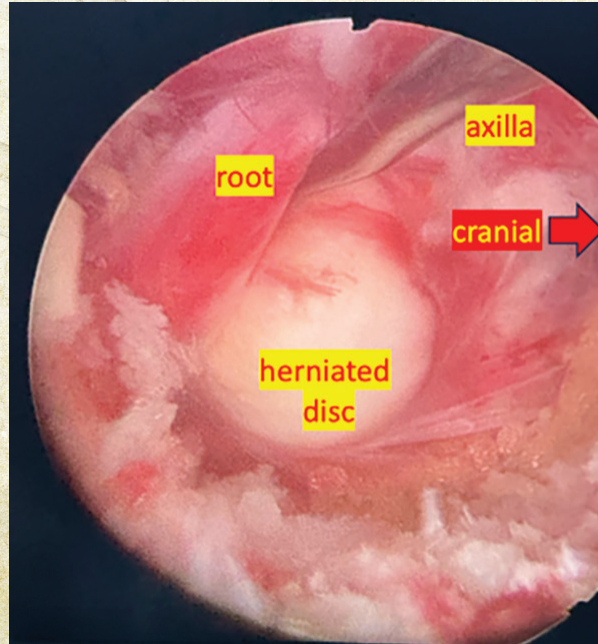




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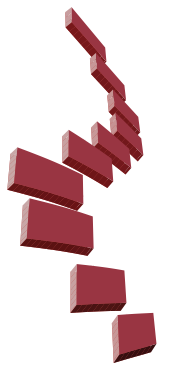


OCTOBER
2026

► VOLUME: 37

► ISSUE: 4





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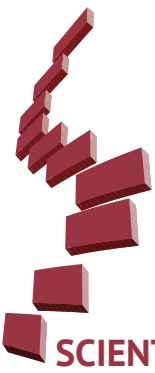
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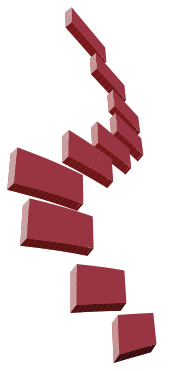


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Web: www.galenos.com.tr
Publisher Certificate Number: 14521

Printing Date: October 2026

E-ISSN 2147-5903

International scientific journal published quarterly.



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Contemporary spine surgery is increasingly shaped by a more comprehensive understanding of patients, in which clinical symptoms, radiological parameters, surgical techniques, perioperative management, and patient-reported outcomes are considered together. The current issue of the Journal of Turkish Spinal Surgery reflects this evolving perspective through a diverse collection of studies addressing spinal health across different age groups, pathologies, and stages of treatment. Although the studies presented in this issue focus on distinct clinical questions, they share a common message: meaningful advances in spine care require attention not only to surgical correction, but also to how spinal disorders are assessed, treated, and experienced by patients.

Assessment of spinal alignment is an important component of this broader perspective. The exploratory study evaluating agreement among adolescents, parents, and an expert in the visual assessment of adolescent posture highlights an often-underappreciated aspect of spinal health: the perception of posture. Objective radiographic measurements remain fundamental, but patients and families frequently interpret spinal appearance before formal medical evaluation. Understanding differences between these perspectives may contribute to earlier recognition of postural abnormalities and improve communication between clinicians, adolescents, and their families.

The issue also addresses the expanding role of less invasive surgical strategies. The study examining spinal anesthesia for unilateral biportal endoscopic lumbar decompression in patients with significant comorbidities explores an approach that may be particularly relevant for patients in whom general anesthesia presents additional challenges. Similarly, the comparison of pre-incisional caudal epidural analgesia with local surgical-site infiltration after lumbar microdiscectomy emphasizes the importance of perioperative pain management. These studies reflect a broader movement toward reducing physiological stress, facilitating recovery, and tailoring perioperative strategies to individual patient characteristics.

Motion preservation remains another important topic in contemporary cervical spine surgery. The retrospective comparison of cervical disc arthroplasty and anterior cervical discectomy and fusion provides insight into the temporal evolution of surgical outcomes. The observation of early differences in motion preservation followed by convergence of outcomes at two years illustrates an important principle in interpreting surgical literature: early biomechanical advantages do not necessarily translate directly into differences in intermediate-term clinical outcomes. Long-term follow-up therefore remains essential when evaluating technologies designed to modify spinal biomechanics.

The relationship between spinal morphology and degeneration is further explored through the investigation of sacral morphological parameters and lower lumbar disc degeneration. Such studies remind us that degenerative spinal disease should not be considered solely as a consequence of age or external mechanical factors. Individual anatomical characteristics may influence segmental biomechanics and potentially contribute to disease development. Continued investigation of these relationships may help move spine care toward more individualized risk assessment.

Patient-related factors are also represented by the study investigating sleep quality and cervical alignment in individuals with chronic neck pain. Pain, sleep, spinal alignment, and functional status are closely interconnected, yet these dimensions are often evaluated separately in clinical practice. Incorporating such patient-centered variables may provide a more complete understanding of chronic spinal disorders and help clinicians recognize factors that may influence symptom persistence and recovery.

Finally, the comparison of postoperative day-one versus delayed early magnetic resonance imaging following intradural spinal tumor surgery addresses an important practical question in postoperative surveillance. Determining when imaging provides clinically meaningful information while avoiding unnecessary investigations remains relevant to both patient care and healthcare resource utilization.

Taken together, the studies in this issue demonstrate that progress in spinal surgery is not defined by surgical innovation alone. It also depends on improving assessment, refining perioperative care, understanding individual anatomical and patient-related factors, and interpreting outcomes over an appropriate time horizon. Future research should continue to integrate objective measurements with patient-centered outcomes and longer-term follow-up.

The Journal of Turkish Spinal Surgery is pleased to present these contributions as part of the continuing effort to promote clinically relevant, scientifically rigorous, and patient-oriented research in spinal disorders. We hope that the studies in this issue will stimulate further discussion and prospective investigation while contributing to the ongoing evolution of contemporary spine care.

Co-Editor-in-Chief

Ömer Erşen, M.D.,



POSTOPERATIVE DAY 1 VERSUS DELAYED EARLY MAGNETIC RESONANCE IMAGING AFTER INTRADURAL SPINAL TUMOR SURGERY

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ABSTRACT

Objective: Postoperative magnetic resonance imaging (MRI) is important after intradural spinal tumor surgery, but the optimal timing of early postoperative imaging is not standardized. This study compared postoperative day 1 (POD1) MRI with delayed early MRI in detecting residual tumor.

Materials and Methods: This retrospective single center cohort included patients who underwent surgery for intradural spinal tumors between June 2020 and December 2025. Patients who underwent gadolinium-enhanced POD1 MRI and delayed early gadolinium-enhanced MRI (performed within POD30-60) were analyzed. Patient-level timing of delayed early MRI was recorded. Two blinded, spine-focused neurosurgeons reviewed MRI studies using predefined criteria.

Results: Ninety-six patients from a 112-patient intradural spinal tumor cohort had paired imaging. Sixteen patients were excluded because of missing MRI studies. A delayed early MRI was obtained a median of 48 days after surgery (interquartile range, 41-56; range, 33-60). POD1 and delayed early MRI were concordant with respect to the presence of residual tumor in 95 of 96 patients. With delayed early MRI as the paired imaging comparator, POD1 MRI demonstrated 93.3% sensitivity, 100.0% specificity, 98.8% negative predictive value, 99.0% accuracy, and a kappa coefficient of 0.959. Progression occurred in 7 of 13 patients (53.8%) with POD1 residual tumor and in 1 of 81 patients (1.2%) without POD1 residual tumor ($p<0.001$).

Conclusion: POD1 gadolinium-enhanced MRI showed very high agreement with delayed early MRI in detecting residual tumor after intradural spinal tumor surgery and may serve as a reliable early baseline for residual tumor assessment. However, cerebrospinal fluid (CSF) collection and T2 signal change were more time-dependent findings, supporting selective delayed imaging when early findings are equivocal or postoperative symptoms or CSF-related concerns persist.

Keywords: Spinal cord neoplasms, magnetic resonance imaging, postoperative period, residual neoplasm, disease progression

INTRODUCTION

Postoperative magnetic resonance imaging (MRI) is used after intradural spinal tumor surgery to document extent of resection (EOR), establish a surveillance baseline, and support follow-up or adjuvant treatment decisions in selected patients^(1,2). Accurate residual tumor assessment is particularly relevant for tumor types in which subtotal resection is associated with recurrence or progression, including spinal ependymomas, myxopapillary ependymomas, meningiomas, and other intradural lesions⁽²⁻⁴⁾. However, the timing used to define postoperative EOR after intradural spinal tumor surgery remains inconsistent. In both intradural extramedullary (IDEM) and intramedullary (IM) tumor literature, some studies use early postoperative MRI within 72 hours, whereas others rely on delayed first follow-up MRI obtained approximately 3-6 months after surgery⁽⁵⁻⁸⁾.

This variation limits comparison between surgical series and leaves a practical question: whether immediate postoperative MRI provides the same residual tumor information as delayed early imaging.

In cranial glioma surgery, postoperative MRI timing has been studied more extensively. Early postoperative MRI is used to assess residual enhancing tumor before surgically induced enhancement becomes more prominent, although interpretation may be confounded by blood products, ischemia related diffusion restriction, reactive enhancement, and postoperative T2 or fluid attenuated inversion recovery changes⁽⁹⁻¹¹⁾. Comparable evidence is limited for intradural spinal tumor surgery, where the imaging problem may differ from cranial intra-axial tumors because many IDEM lesions are extra-axial, well circumscribed, and contrast enhancing, whereas IM tumors may involve intrinsic cord tissue and may be more difficult to distinguish from postoperative neural tissue changes⁽¹²⁻¹⁴⁾.

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Received: 09.06.2026 **Accepted:** 30.07.2026 **Publication Date:** 14.10.2026

Cite this article as: Baydar AT, Bayındır M. Postoperative day 1 versus delayed early magnetic resonance imaging after intradural spinal tumor surgery. J Turk Spinal Surg. 2026;37(4):134-141



Postoperative day 1 (POD1) and delayed early MRI may also differ according to the postoperative feature being assessed. Residual enhancing tumor may be a relatively stable finding, whereas cerebrospinal fluid (CSF) collection, postoperative hematoma, residual compression, syrinx, and T2 signal change may evolve over the first postoperative weeks⁽¹⁵⁾. Therefore, POD1 MRI may be reliable for residual tumor but less reliable for dynamic postoperative findings.

The primary objective of this study was to compare POD1 gadolinium-enhanced MRI with delayed early postoperative MRI after intradural spinal tumor surgery for residual tumor detection. Delayed early MRI corresponded to the institutional 6-week postoperative control MRI and was defined as contrast-enhanced MRI obtained between POD30 and 60. Secondary objectives were to compare agreement for selected dynamic postoperative MRI findings and to assess the association between POD1 residual tumor and subsequent radiological progression.

MATERIALS AND METHODS

Study Design and Patient Selection

This retrospective single-center cohort study was performed at a tertiary neurosurgical center after approval by the University of Health Sciences Türkiye, Başakşehir Çam and Sakura City Hospital Local Ethics Committee (approval no: KAEK/04.02.2026.78, date: 24.02.2026). The requirement for individual informed consent was waived because of the retrospective design and anonymized analysis.

Patients who underwent surgery for intradural spinal tumors between June 2020 and December 2025 were reviewed. The eligible intradural spinal tumor cohort consisted of 112 patients. Patients were eligible for the paired imaging analysis if both POD1 gadolinium-enhanced MRI and delayed early postoperative gadolinium-enhanced MRI were available. Delayed early MRI was defined a priori as MRI performed between POD30 and 60. Sixteen patients were excluded because delayed early MRI was unavailable within this predefined window, leaving 96 patients in the final paired MRI cohort. Patient-level delayed early MRI timing was recorded for all included patients.

During the study period, the institutional postoperative imaging protocol included routine POD1 MRI to document immediate postoperative findings and an outpatient control visit with delayed early MRI at approximately 6 weeks after surgery.

Surgical Treatment and Clinical Variables

All operations were performed using standard microsurgical techniques. The surgical approach and EOR were selected according to tumor level, compartment, preoperative imaging, suspected pathology, and intraoperative findings. The operative goal was maximal safe resection. Subtotal resection was accepted when further removal was considered unsafe because

of IM location, adherence to functional neural tissue, vascularity, or intraoperative neuromonitoring change.

Demographic, clinical, operative, pathological, and outcome variables were extracted from the institutional dataset. Clinical variables included age, sex, American Society of Anesthesiologists physical status score, comorbidities, preoperative and postoperative neurological status, operative duration, transfusion, length of stay, readmission, reoperation, and follow up duration. Neurological status was recorded using the modified McCormick scale⁽¹⁶⁾.

Histopathological diagnoses were grouped as meningioma, schwannoma/peripheral nerve sheath tumor, non-myxopapillary ependymoma, myxopapillary ependymoma, congenital/cystic lesions, glial or malignant tumors, vascular lesions, and other rare tumors. Tumor compartment was classified anatomically as IDEM or IM according to the imaging and operative record. For pathology grouping, ependymal tumors with IM location were classified as non-myxopapillary ependymomas, whereas ependymal tumors with non-IM location were classified as myxopapillary ependymomas.

MRI Protocol and Image Assessment

All examinations used for residual tumor assessment included gadolinium-enhanced sagittal and axial T1-weighted sequences. Sagittal and axial T2-weighted images were used for anatomical correlation and for assessment of syrinx, cord signal change, and postoperative fluid collection. Residual tumor was assessed only on contrast-enhanced MRI.

Preoperative tumor length, maximal axial diameter, foraminal extension, syrinx, dural tail, and T2 hyperintensity were recorded using predefined criteria. Ventral relationship was classified on axial images according to the dominant anterior-half relationship of the lesion to the dural sac or spinal canal for IDEM tumors, or the anterior-half epicenter within the cord for IM tumors. Borderline cases were resolved by consensus review.

POD1 MRI variables included residual tumor, postoperative hematoma, residual compression, T2 signal change, and CSF collection. Delayed early MRI variables included residual tumor, syrinx, T2 signal change, and CSF collection.

Residual Tumor Definition

Residual tumor was defined as nodular, mass like, or anatomically persistent enhancing tissue at the surgical level that was compatible with the preoperative tumor and spatially concordant with the original tumor location. Linear dural enhancement alone, non-specific granulation tissue, hemostatic material, blood products, collapsed tumor capsule, postoperative packing, and simple CSF or fluid collection were not classified as residual tumor. Equivocal enhancement was adjudicated by consensus after review of preoperative morphology, operative level, and multiplanar postcontrast sequences.

Postoperative hematoma was defined as a blood-product collection at the operative level on POD1 MRI. Residual

compression was defined as persistent mass effect on the spinal cord, conus, or cauda equina after surgery. T2 signal change was defined as IM hyperintensity at or adjacent to the operative level. CSF collection was defined as an extradural, subfascial, or paraspinal postoperative fluid collection compatible with CSF accumulation or pseudomeningocele.

MRI Review and Interrater Reliability

MRI features were independently reviewed by two spine-focused neurosurgeons using the predefined criteria. Reviewers were blinded to clinical outcomes, tumor progression, reoperation status, pathology, and each other's ratings. When reviewing POD1 MRI, reviewers were also blinded to the delayed early MRI result. Preoperative images were available for anatomical correlation and to confirm the original tumor level and morphology, but operative reports and later clinical outcomes were not used for the primary residual tumor classification. Discrepancies were resolved by consensus review.

Interrater reliability was assessed in a random subset of 45 patients using exact agreement. For POD1 MRI, exact agreement was 44/45 for residual tumor (97.8%), 43/45 for hematoma (95.6%), 45/45 for residual compression (100.0%), 44/45 for T2 signal change (97.8%), and 43/45 for CSF collection (95.6%). For delayed early MRI, exact agreement was 45/45 for residual tumor (100.0%), 45/45 for syrinx (100.0%), 44/45 for T2 signal change (97.8%), and 44/45 for CSF collection (97.8%). Because the archived reliability dataset preserved exact agreement counts but not the full rater-level contingency tables, kappa statistics were not calculated for the interrater subset.

Outcomes

The primary outcome was agreement between POD1 and delayed early MRI for residual tumor detection. Delayed early MRI was treated as a comparator, not as an absolute gold standard.

Secondary imaging outcomes were agreement between POD1 and delayed early MRI for CSF collection and T2 signal change. Secondary clinical outcomes included radiological tumor progression, tumor reoperation, any reoperation, readmission, and composite postoperative morbidity.

Progression analysis included only patients with postoperative surveillance beyond delayed early MRI. Two patients without adequate follow-up imaging beyond delayed early MRI were excluded from the progression analysis. Progression was defined as radiological enlargement of residual tumor compared with POD1 or delayed early MRI, or new recurrent tumor after no residual tumor had been identified on POD1 or delayed early MRI.

Composite postoperative morbidity was defined as any reoperation, lumbar drain placement for CSF fistula, or postoperative neurological worsening during the index postoperative period.

Statistical Analysis

Continuous variables were summarized as medians and interquartile ranges (IQRs). Categorical variables were summarized as counts and percentages. Agreement between POD1 and delayed early MRI findings was evaluated using paired 2×2 contingency tables, McNemar tests, and Cohen kappa. Diagnostic performance of POD1 MRI was calculated using delayed early MRI as the comparator and included sensitivity, specificity, positive predictive value, negative predictive value, and accuracy. These metrics therefore describe agreement relative to delayed early MRI rather than diagnostic accuracy against a pathological gold standard.

Associations between residual tumor status and categorical clinical outcomes were evaluated using Fisher's exact tests. Continuous variables were compared using Wilcoxon rank-sum tests. Logistic regression was considered exploratory but was not emphasized because of sparse event counts and complete or quasi-complete separation in some models. A two-sided p-value <0.05 was considered statistically significant. Statistical analyses were performed using R software (version 4.5.2).

RESULTS

Cohort Characteristics

Of the 112 patients in the eligible postoperative imaging cohort, 96 had both gadolinium-enhanced POD1 MRI and delayed early MRI within POD30-60 and were included in the paired imaging analysis. Sixteen patients were excluded because delayed early MRI was unavailable within the predefined window. Delayed early MRI was obtained at a median of 48 days after surgery (IQR, 41-56; range, 33-60).

The median age was 49.5 years (IQR, 38.0-59.0), and 58 patients (60.4%) were female. Median tumor length was 18.5 mm (IQR, 13.8-27.6), median axial diameter was 10.8 mm (IQR, 9.0-13.4), median operative time was 240 minutes (IQR, 188-311), and median length of stay was 4 days (IQR, 3-6). Median follow-up was 13.1 months (IQR, 6.9-24.9). Pathological and anatomical distributions are summarized in Table 1.

Residual Tumor Agreement Between POD1 and Delayed Early MRI

POD1 MRI identified residual tumor in 14 of 96 patients (14.6%), whereas delayed early MRI identified residual tumor in 15 of 96 patients (15.6%). Residual tumor classification was concordant in 95 of 96 patients. One patient had no definite residual tumor on POD1 MRI but had residual tumor on delayed early MRI (Figure 1). No patient had residual tumor on POD1 MRI that was absent on delayed early MRI.

Using delayed early MRI as the comparator, POD1 MRI showed 93.3% sensitivity, 100.0% specificity, 100.0% positive predictive value, 98.8% negative predictive value, and 99.0% accuracy for residual tumor detection. Cohen's kappa was 0.959, and

Table 1. Baseline characteristics of the paired POD1/delayed early MRI cohort

Variable	Value
Cohort and imaging timing	
Patients, n	96
Delayed early MRI timing, POD	48 (41-56); range 33-60
Delayed early MRI POD30-39	18 (18.8)
Delayed early MRI POD40-49	36 (37.5)
Delayed early MRI POD50-60	42 (43.8)
Demographic and operative characteristics	
Age, years	49.5 (38.0-59.0)
Female sex	58 (60.4)
Tumor length, mm	18.5 (13.8-27.6)
Axial diameter, mm	10.8 (9.0-13.4)
Operative time, min	240 (188-311)
Length of stay, days	4 (3-6)
Follow-up, months	13.1 (6.9-24.9)
Postoperative imaging and progression	
POD1 residual tumor	14 (14.6)
Delayed early MRI residual tumor	15 (15.6)
Progression among patients with available data	8/94 (8.5)
Pathology	
Meningioma	34 (35.4)
Schwannoma/PNST	28 (29.2)
Non-myxopapillary ependymoma	6 (6.3)
Myxopapillary ependymoma	18 (18.8)
Glial/malignant	5 (5.2)
Congenital/cystic	3 (3.1)
Other rare	1 (1.0)
Vascular	1 (1.0)
Tumor compartment and level	
IDEM	86 (89.6)
IM	10 (10.4)
Thoracic	37 (38.5)
Cervical	28 (29.2)
Lumbar	21 (21.9)
Conus	8 (8.3)
Other/sacral or lumbosacral	2 (2.1)

Values are presented as median (interquartile range) or n (%), unless otherwise indicated. Two patients without adequate follow-up imaging beyond delayed early MRI were excluded from the progression analysis. IDEM: Intradural extramedullary, IM: Intramedullary, MRI: Magnetic resonance imaging, PNST: Peripheral nerve sheath tumor, POD: Postoperative day

the McNemar test was not significant ($p=1.000$). Paired MRI classification matrices and diagnostic performance metrics are summarized separately in Figure 2A and Table 2.

Secondary MRI Findings

Agreement was lower for dynamic postoperative MRI findings than for residual tumor. For CSF collection, findings were concordant in 84 of 96 patients; discordance occurred in

both directions, with collections resolving after POD1 MRI in some patients and becoming apparent on delayed early MRI in others. For T2 signal change, findings were concordant in 82 of 96 patients, with most discordance reflecting early POD1 signal change that was no longer present on delayed early MRI. Diagnostic performance for these secondary MRI findings is shown in Table 2.

Pathology and Compartment Specific Findings

Pathology and compartment specific findings are summarized in Table 3. POD1 residual tumor was observed most frequently among glial/malignant, congenital/cystic, and vascular lesions, although these subgroup findings were descriptive because of limited event counts. Among 86 IDEM tumors, residual tumor classification was concordant in 85 patients (98.8%). Among 10 IM tumors, residual tumor classification was concordant in all patients.

POD1 Residual Tumor and Clinical Outcomes

Progression data were available for 94 patients. Radiological progression occurred in 8 patients (8.5%). Progression was observed in 7 of 13 patients (53.8%) with POD1 residual tumor and 1 of 81 patients (1.2%) without POD1 residual tumor ($p<0.001$; Figure 2B). Using delayed early MRI residual tumor status, progression occurred in 7 of 14 patients (50.0%) with residual tumor and 1 of 80 patients (1.3%) without residual tumor ($p<0.001$).

POD1 residual tumor was associated with a higher rate of any reoperation and showed a numerically higher rate of tumor reoperation. Readmission and composite postoperative morbidity were also numerically higher but did not reach statistical significance. Clinical and imaging outcomes according to POD1 residual tumor status are summarized in Supplementary Table 1. In retrospective chart review, no patient with negative POD1 MRI for residual tumor had documentation indicating that delayed early MRI alone prompted reoperation, readmission, adjuvant-treatment referral, or a change in surveillance strategy.

DISCUSSION

This study found that POD1 gadolinium-enhanced MRI classified residual tumor almost identically to delayed early MRI after intradural spinal tumor surgery. Among 96 patients with paired imaging, residual tumor classification was concordant in 95 patients, with a kappa of 0.959. POD1 MRI missed one small residual focus that was visible on delayed early MRI, and no POD1 residual-tumor finding disappeared on the delayed early study. These findings support POD1 MRI as a reliable early baseline for residual tumor and EOR assessment.

The timing of postoperative MRI after intradural spinal tumor surgery is not standardized. Ependymal tumor guidance and contemporary spinal tumor series recognize postoperative MRI as important for residual disease assessment and surveillance, but the imaging time point used to define postoperative residual tumor varies substantially, ranging from early MRI within 24-72 hours to first follow up MRI obtained approximately 3 months after surgery^(1,5,8). In the present cohort, delayed early MRI was defined a priori for analysis as POD30-60, and patient level scan timing confirmed a median postoperative timing of 48 days. This timing transparency is important because EOR is frequently analyzed as a prognostic variable, yet the imaging time point used to define it may differ between cohorts.

The main novelty of the study is not the observation that residual tumor is associated with progression, which is biologically and clinically expected in several intradural tumor types. Rather, the important finding is that POD1 MRI already captured nearly the same residual tumor classification as delayed early MRI and identified the same clinically relevant residual tumor group. Progression occurred in 53.8% of patients with POD1 residual tumor compared with 1.2% of patients without POD1 residual tumor. This finding is consistent with the general literature linking residual disease and EOR to recurrence or progression risk in several intradural tumor groups, including ependymoma, myxopapillary ependymoma, and meningioma^(1-4,8). However, this association should be interpreted as supportive clinical correlation rather than independent prognostic modeling because progression events were sparse, pathology specific risks differed across the heterogeneous cohort, adjuvant treatment was variable, and follow up intensity may have differed according to postoperative findings.

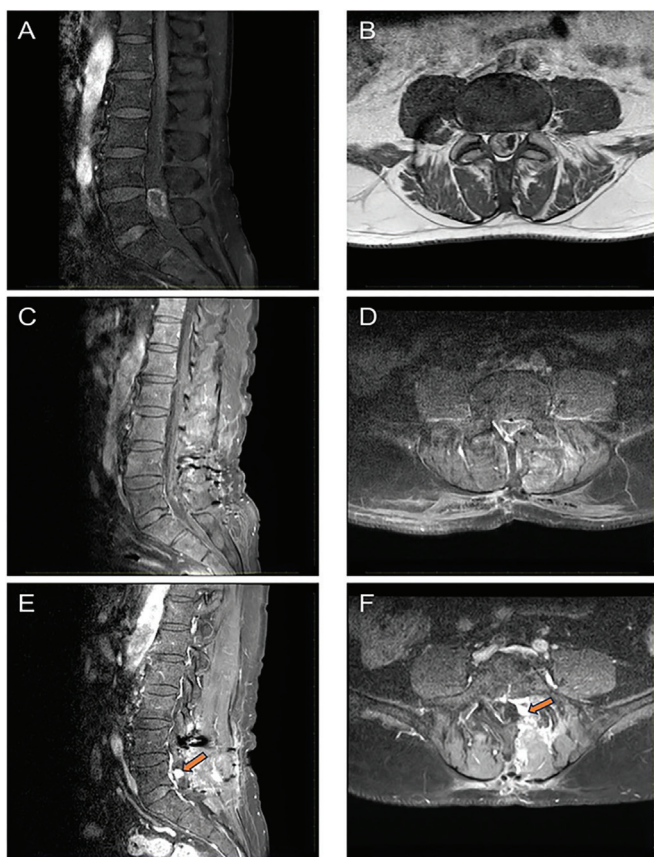


Figure 1. Illustrative discordant paired postoperative MRI case. Preoperative sagittal and axial contrast-enhanced images demonstrate the index intradural lesion (A, B). POD1 sagittal and axial images show postoperative change without definite residual tumor (C, D). Delayed early sagittal and axial images demonstrate a small enhancing residual focus at the operative level, indicated by arrows (E, F). This case illustrates the single discordant residual-tumor classification between POD1 and delayed early MRI. MRI: Magnetic resonance imaging, POD1: Postoperative day 1

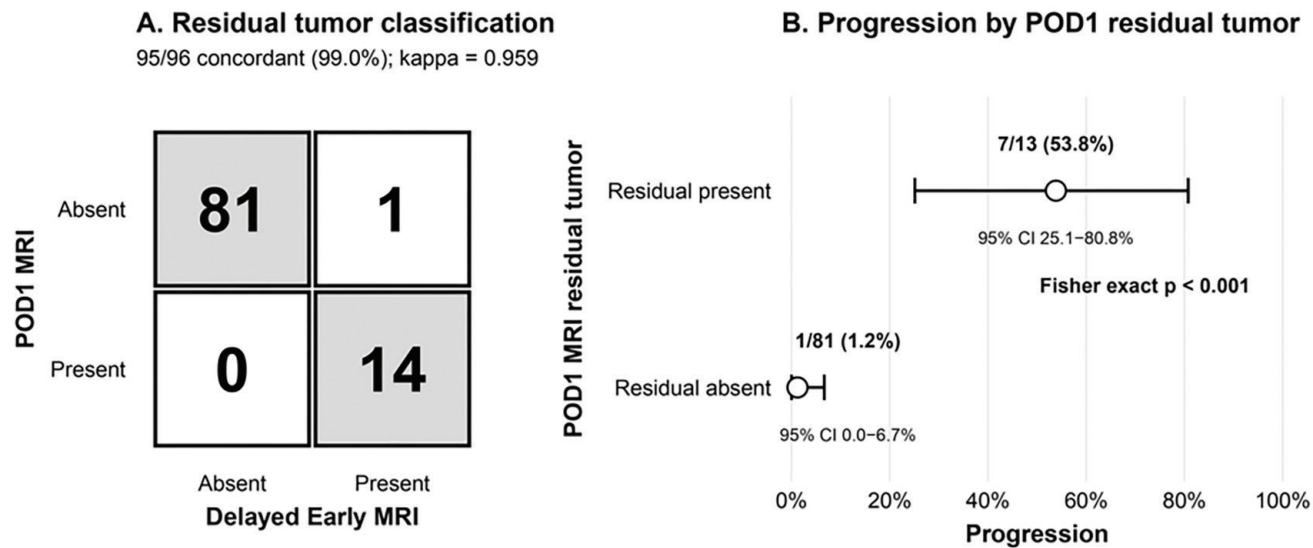


Figure 2. POD1 residual tumor assessment: agreement with delayed early MRI and association with progression
(A) Paired residual tumor classification on POD1 and delayed early gadolinium-enhanced MRI. The delayed early MRI refers to the MRI obtained within postoperative days 30-60. Residual tumor classification was concordant in 95 of 96 patients (99.0%; kappa=0.959). Kappa refers to agreement between POD1 and delayed early MRI classifications, not interrater reliability. (B) Progression according to POD1 residual tumor status among patients with surveillance beyond delayed early MRI. Points indicate observed progression risk, and horizontal bars indicate exact binomial 95% CIs. Progression occurred in 1 of 81 patients (1.2%; 95% CI, 0.0-6.7%) without POD1 residual tumor and 7 of 13 patients (53.8%; 95% CI, 25.1-80.8%) with POD1 residual tumor ((Fisher's exact p<0.001). MRI: Magnetic resonance imaging, POD1: Postoperative day 1, CI: Confidence interval

Table 2. Agreement-derived performance of POD1 MRI using delayed early MRI as comparator

MRI finding	Sensitivity, % (95% CI)	Specificity, % (95% CI)	PPV, % (95% CI)	NPV, % (95% CI)	Accuracy, % (95% CI)	Kappa	McNemar p
Residual tumor	93.3 (68.1-99.8)	100.0 (95.5-100.0)	100.0 (76.8-100.0)	98.8 (93.4-100.0)	99.0 (94.3-100.0)	0.959	1.000
CSF collection	50.0 (23.0-77.0)	93.9 (86.3-98.0)	58.3 (27.7-84.8)	91.7 (83.6-96.6)	87.5 (79.2-93.4)	0.467	0.774
T2 signal change	91.3 (72.0-98.9)	83.6 (73.0-91.2)	63.6 (45.1-79.6)	96.8 (89.0-99.6)	85.4 (76.7-91.8)	0.652	0.013

Diagnostic performance metrics use delayed early MRI as the paired imaging comparator, not as an absolute pathological gold standard. Sensitivity, specificity, PPV, NPV, and accuracy are presented as percentages with exact binomial 95% confidence intervals (CIs). CSF: Cerebrospinal fluid, MRI: Magnetic resonance imaging, PPV: positive predictive value, NPV: Negative predictive value, POD1: Postoperative day 1

The reliability of POD1 MRI did not extend equally to dynamic postoperative findings. Agreement for CSF collection and T2 signal change was lower than agreement for residual tumor. POD1 MRI had only 50.0% sensitivity for CSF collection visible on delayed early MRI, and discordance occurred in both directions. This pattern is clinically plausible because postoperative CSF collections may enlarge, resolve, or become more apparent after discharge. T2 signal change also evolved between time points, with some early signal changes resolving and a smaller number appearing or becoming more visible later. These findings support a practical distinction between relatively stable residual enhancing tumor and more dynamic postoperative imaging findings.

The cranial tumor literature provides an important analogy but should not be directly extrapolated to spinal intradural tumors. In glioma surgery, early postoperative MRI timing is critical because surgically induced enhancement, ischemic

change, and evolving T2/fluid-attenuated inversion recovery abnormalities can affect residual tumor assessment⁽⁹⁻¹¹⁾. Intradural spinal tumors differ anatomically and radiologically. Many IDEM lesions are extra axial, well circumscribed, and contrast enhancing, which may make residual tumor more distinguishable from postoperative change on early imaging. In contrast, IM tumors involve intrinsic cord tissue, and infiltrative or poorly demarcated lesions may create interpretive difficulties more similar to intra axial brain tumors⁽¹²⁻¹⁴⁾.

These findings have practical implications for postoperative workflow. POD1 MRI provides immediate documentation before discharge, establishes a baseline for future surveillance, and may allow earlier multidisciplinary discussion when residual tumor is present. Among patients without residual tumor on POD1 MRI, chart review did not identify any documented treatment, reoperation, readmission, or surveillance plan change that was attributed solely to the delayed early MRI. This does not mean that

Table 3. Pathology and compartment specific residual tumor agreement and progression

Subgroup	n	POD1 residual tumor	Delayed early MRI residual tumor	Concordant residual classification	Progression
Meningioma	34	4/34 (11.8)	4/34 (11.8)	34/34 (100.0)	2/34 (5.9)
Schwannoma/PNST	28	3/28 (10.7)	4/28 (14.3)	27/28 (96.4)	2/28 (7.1)
Non-myxopapillary ependymoma	6	0/6 (0.0)	0/6 (0.0)	6/6 (100.0)	0/6 (0.0)
Myxopapillary ependymoma	18	1/18 (5.6)	1/18 (5.6)	18/18 (100.0)	1/17 (5.9)
Glial/malignant	5	3/5 (60.0)	3/5 (60.0)	5/5 (100.0)	3/5 (60.0)
Congenital/cystic	3	2/3 (66.7)	2/3 (66.7)	3/3 (100.0)	0/2 (0.0)
Other rare	1	0/1 (0.0)	0/1 (0.0)	1/1 (100.0)	0/1 (0.0)
Vascular	1	1/1 (100.0)	1/1 (100.0)	1/1 (100.0)	0/1 (0.0)
IDEM	86	10/86 (11.6)	11/86 (12.8)	85/86 (98.8)	6/84 (7.1)
IM	10	4/10 (40.0)	4/10 (40.0)	10/10 (100.0)	2/10 (20.0)

Values are presented as n (%), unless otherwise indicated. Subgroup findings are descriptive and were not intended for inferential comparison because of limited event counts. The glial/malignant category comprised glioblastoma (n=1), diffuse midline glioma, H3K27-altered (n=1), diffuse astrocytoma (n=1), high-grade diffuse glial tumor (n=1), and a neuroendocrine tumor reported as paraganglioma versus metastasis (n=1). The congenital/cystic category comprised mature teratoma (n=1), mature cystic teratoma (n=1), and dermoid tumor (n=1). The other rare category comprised extranodal Rosai-Dorfman disease (n=1). The vascular category comprised hemangioblastoma (n=1). IDEM: Intradural extramedullary, IM: Intramedullary, MRI: Magnetic resonance imaging, PNST: Peripheral nerve sheath tumor, POD: Postoperative day

delayed early MRI is unnecessary for all patients. Rather, POD1 MRI appears most useful for residual tumor and EOR documentation, whereas delayed early MRI may be reserved for equivocal early imaging, evolving symptoms, suspected CSF related complications, or unresolved postoperative cord-signal questions.

Study Limitations

Several limitations should be considered. First, the study was retrospective and single center. Second, only patients with paired POD1 and delayed early MRI within the predefined POD30-60 window were included in the main analysis, which may introduce selection bias. Third, although patient-level delayed early MRI timing was available for all included patients, the cohort was not large enough to meaningfully assess whether agreement differed across narrower timing intervals within the POD30-60 window. Fourth, the cohort included heterogeneous tumor pathologies and both IDEM and IM tumors, reflecting real world intradural spinal tumor practice but limiting pathology specific inference. Fifth, delayed early MRI was used as a comparator rather than an absolute gold standard. Sixth, residual tumor was analyzed as a binary variable rather than volumetrically. Seventh, although both reviewers were spine-focused neurosurgeons familiar with postoperative intradural tumor imaging, independent neuroradiology review was not performed. Finally, progression events were relatively few, limiting multivariable modeling, and the association between residual tumor and progression should be considered descriptive and exploratory.

CONCLUSION

POD1 gadolinium-enhanced MRI showed very high agreement with delayed early MRI for residual tumor detection after

intradural spinal tumor surgery. These findings support POD1 MRI as a reliable early baseline for residual tumor and EOR assessment. However, agreement was lower for CSF collection and T2 signal change, indicating that delayed early MRI remains useful when early findings are equivocal or when postoperative symptoms, CSF related concerns, or cord-signal abnormalities require further evaluation. The association between POD1 residual tumor and later radiological progression should be interpreted descriptively because of sparse events and pathology heterogeneity.

Ethics

Ethics Committee Approval: This retrospective single-center cohort study was performed at a tertiary neurosurgical center after approval by the University of Health Sciences Türkiye, Başakşehir Çam and Sakura City Hospital Local Ethics Committee (approval no: KAEK/04.02.2026.78, date: 24.02.2026).

Informed Consent: The requirement for individual informed consent was waived because of the retrospective design and anonymized analysis.

Footnotes

During the preparation of this manuscript, the authors used ChatGPT (OpenAI, San Francisco, USA) only for language editing and structural refinement during manuscript preparation. All content, data interpretation, statistical analyses, and conclusions were reviewed and verified by the authors, who take full responsibility for the final manuscript.

Authorship Contributions

Surgical and Medical Practices: A.T.B., M.B., Concept: A.T.B., Design: A.T.B., Data Collection or Processing: A.T.B., M.B.,

Analysis or Interpretation: A.T.B., M.B., Literature Search: A.T.B., M.B., Writing: A.T.B., M.B.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study received no financial support.

Supplementary Table Link: <https://d2v96fxpocvxx.cloudfront.net/6548c443-00ef-4a8c-a306-c0848f02b51f/content-images/846d5144-ed95-4dd8-a9e2-1123c5d6bbb5.pdf>

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IMPACT OF SACRAL MORPHOLOGICAL PARAMETERS ON L4-5 AND L5-S1 INTERVERTEBRAL DISC DEGENERATION: THE ROLE OF SACRAL TABLE ANGLE

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ABSTRACT

Objective: This study aims to investigate the correlation between sacral morphological parameters and degeneration of the L4-5 and L5-S1 discs, with particular emphasis on STA and SI.

Materials and Methods: This retrospective cohort study includes patients who were admitted with back pain and/or radicular pain. Degeneration at L4-5 and L5-S1 was evaluated using Pfirrmann grading on lumbar magnetic resonance imaging. Pfirrmann grades 1-2 were considered non-degenerative, while Pfirrmann grades 3-5 were considered degenerative. Pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS), lumbar lordosis (LL), LL distribution index (LLDI), sacral inclination (SI), and sacral table angle (STA) were measured from standing lumbosacral X-rays.

Results: Ninety consecutive patients were included and the mean age was 47.42±9.84. Fifty-four patients were female and 36 were male. Disc degeneration was observed at L4-5 in 44 patients (48.9%) and at L5-S1 in 47 patients (52.2%). Degeneration at both disc levels was observed in 38 patients. PI, PT, and SS were significantly higher, whereas LLDI, SI, and STA were significantly lower in patients with two-level disc degeneration. There was no statistically significant difference in LL between the degenerative and non-degenerative groups. SI was negatively correlated with Pfirrmann grades in both L4-5 and L5-S1. STA showed a stronger negative correlation with Pfirrmann grades at both levels. The intensity of degeneration was inversely correlated with STA. The mean STA values were 105.09±3.09° in no degeneration, 100.01±4.00° in single-level degeneration and 95.85±4.17° in two-level degeneration groups.

Conclusion: Sacral morphology shows significant association with lower lumbar disc degeneration. A lower STA value is associated with increased disc degeneration at the L4-L5 and L5-S1 levels. STA may be a morphological parameter reflecting the biomechanical environment of the lumbosacral junction.

Keywords: Lumbar disc degeneration, sacral table angle, sacral inclination, lumbar lordosis, sacral morphology

INTRODUCTION

The complex interactions between spinal curvatures and pelvis are crucial in determining the sagittal alignment of the spine. The concept of “pelvic vertebra” as proposed by Dubousset et al.⁽¹⁾ led to a novel viewpoint for the determination of sagittal profile. Pelvic incidence (PI) is a fixed anatomical parameter that dictates the amount and distribution of lumbar lordosis (LL) necessary for maintaining balanced posture⁽²⁻⁵⁾. It facilitates the determination of the relative position of the sacral plate in relation to the femoral heads⁽⁶⁾. PI is a fundamental measure in surgical planning, especially when predicting the optimal LL. However, very little is known for the components and contributors of PI, which may be related to the variations in sacropelvic anatomy⁽⁷⁾. In addition to PI, the

specific characteristics of sacral morphology are increasingly recognized as important factors influencing biomechanical loading at the lumbosacral junction^(4,5,8).

Several authors proposed different parameters that described the sacral geometry. The sacral slope (SS) and sacral inclination (SI) are positional parameters that may be influenced by postural alterations, and the PI and sacral table angle (STA) are fixed bony anatomical parameters⁽⁸⁾. The STA indicates the orientation of the superior sacral endplate and has been linked to stress related conditions such as spondylolysis and spondylolisthesis⁽⁹⁾. Despite the rising interest in this area, the role of STA in lumbar disc degeneration remains largely unexplored. This study investigates the relationship between the sacral morphological parameters and their impact on the disc degeneration in the lower lumbar segments.

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Received: 12.07.2026 **Accepted:** 09.08.2026 **Publication Date:** 14.10.2026

Cite this article as: Aydın L, Sarıgül B, Topçu A, Özdemir FB, Ramazanoğlu AF. Impact of sacral morphological parameters on L4-5 and L5-S1 intervertebral disc degeneration: the role of sacral table angle. J Turk Spinal Surg. 2026;37(4):142-147



MATERIALS AND METHODS

Study Design and Patient Population

This retrospective observational study included patients that admitted with a low back pain with/without radicular pain. Patients with previous lumbar surgery, spinal trauma, congenital vertebral anomalies, spinal infection, inflammatory spondyloarthropathy, history of spinal trauma and/or fracture, neoplastic disease, scoliosis exceeding 10°, severe spinal stenosis, high-grade spondylolisthesis, lumbosacral transitional anomaly or inadequate radiographic quality were excluded to minimize potential confounding factors affecting spinopelvic alignment. Only examinations with complete radiologic datasets were included in the final analysis. Following application of the eligibility criteria, 90 patients were enrolled for statistical evaluation. Informed consent was obtained from patients and that the ethical approval for this study was obtained from University of Health Sciences Türkiye, Ümraniye Training and Research Hospital Ethical Committee (approval no: 318, date: 23.10.2025).

Radiographic Assessment

In all patients, lumbar magnetic resonance imaging (MRI) was obtained to evaluate the disc degeneration and to determine if there was a disc herniation. Lumbar MRI examinations were independently reviewed to determine the degree of intervertebral disc degeneration at the L4-L5 and L5-S1 levels. Degeneration severity was classified according to the Pfirrmann grading system, a validated MRI-based classification based on disc signal intensity, nucleus-annulus distinction, disc structure, and disc height. Pfirrmann grading included 5 stages of disc degeneration. In this study, the non-degenerated disc composed of Pfirrmann grades 1 and 2, and the degenerated disc category included grades 3, 4 and 5.

In all patients, standing anteroposterior and lateral X-rays along with flexion extension images were obtained. Plain X-rays were used for evaluating the standing sagittal and coronal balance, and spinal instability. Standardized standing lateral lumbosacral radiographs were obtained with patients assuming a comfortable upright posture while maintaining horizontal gaze and full knee extension. All radiographic measurements were performed using a digital picture archiving and communication system by investigators experienced in spinal radiographic assessment.

The following spinopelvic and sacral morphological parameters were recorded:

PI: It is the angle between a line perpendicular to the midpoint of the S1 upper endplate and a line connecting it to the center of the femoral heads.

Pelvic tilt (PT): It is the angle between a vertical line that transects the center of the femoral heads and a line between the center of the femoral heads to the midpoint of S1 upper endplate.

SS: It is the angle between a horizontal line and a line parallel to the S1 upper endplate.

LL: It is the angle between the upper end plate of L1 vertebra and the upper end plate of S1 vertebra.

LL distribution index (LLDI): It is measured via (L4-S1 lordosis/ L1-S1 lordosis) 100.

SI: It is the angle between a vertical line and a line that is parallel to the posterior aspect of the S1 vertebra.

STA: It is the angle between a line that is parallel to the superior end plate of S1 vertebra and a line along the posterior aspect of S1 vertebra. Lower STA values indicate a more horizontally oriented sacral endplate, potentially increasing anterior shear forces at the lumbosacral junction. STA is equal to SI+90-SS (Figure 1).

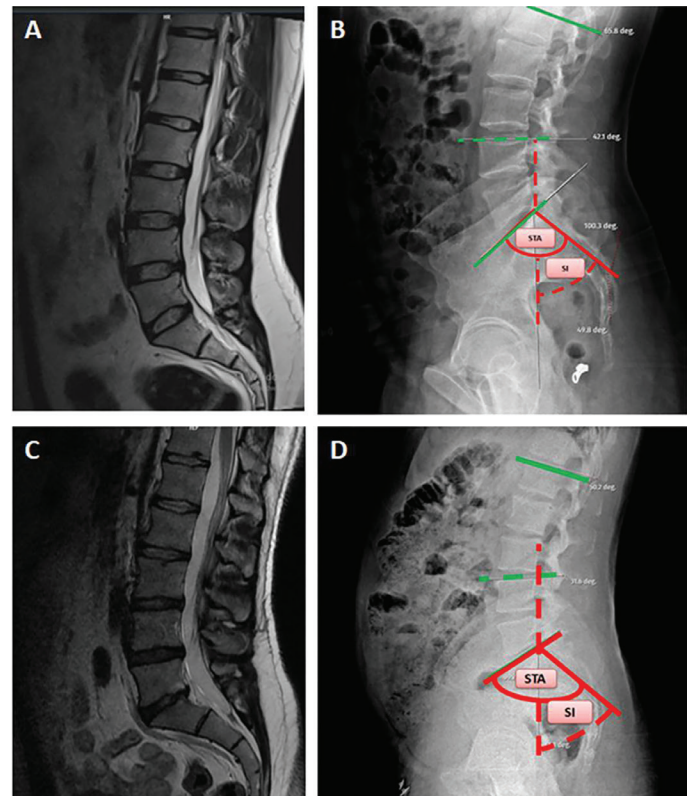


Figure 1. Representative radiological comparison of patients with and without lower lumbar disc degeneration. (A) Sagittal T2-weighted lumbar magnetic resonance imaging (MRI) of a patient with Pfirrmann grade 1 discs at both L4-L5 and L5-S1. (B) Standing lateral lumbar radiograph of the same patient demonstrating the measurements of total lumbar lordosis, distal lumbar lordosis, sacral table angle (STA), and sacral inclination (SI). (C) Sagittal T2-weighted lumbar MRI of a patient with Pfirrmann grade 3 degeneration at L4-L5 and grade 4 degeneration at L5-S1. (D) Standing lateral lumbar radiograph of the same patient demonstrating lower STA and SI values and a less favorable distribution of lumbar lordosis compared with the patient without disc degeneration. The green lines indicate the reference endplates used for lumbar lordosis measurements, whereas the red lines indicate the reference lines used for STA and SI measurements

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics for Windows (IBM Corp., Armonk, NY, USA). Continuous variables were presented as mean $\pm$ standard deviation, and categorical variables as frequencies and percentages. Normality was assessed using the Shapiro-Wilk test. Pfirrmann grades 1-2 were defined as non-degenerated and grades 3-5 as degenerated. Comparisons between degenerated and non-degenerated groups at each disc level were performed using the independent samples t-test or Mann-Whitney U test, as appropriate. Categorical variables were analyzed using the chi-square test or Fisher's exact test. Correlations between radiographic parameters and Pfirrmann grades were evaluated using Pearson or Spearman correlation analysis, as appropriate. For degeneration burden analysis, patients were classified as having no degeneration, single-level degeneration, or two-level degeneration, and groups were compared using one-way analysis of variance or Kruskal-Wallis test. A two-tailed p-value <0.05 was considered statistically significant.

RESULTS

A total of 90 patients met the study criteria and were included in the analysis. The cohort consisted of 54 women (60.0%) and 36 men (40.0%), with a mean age of 47.42 ± 9.84 years. Disc degeneration was observed only at L4-L5 in 6 (6.7%), only at L5-S1 in 9 (10%) and both L4-L5 and L5-S1 in 38 (42.2%) patients. In 37 (41.1%) patients, both disc levels were evaluated as non-degenerative (Table 1).

Comparisons of spinopelvic parameters according to L4-L5 and L5-S1 degeneration status are presented in Tables 2 and

3, respectively. SI showed strong negative correlation with PT ($r=-0.656$, $p<0.001$) and positive correlation with SS ($r=0.297$, $p=0.005$) and LLDI ($r=0.332$, $p=0.001$). SI was also negatively correlated with Pfirrmann grades in both L4-L5 ($r=-0.487$, $p<0.001$) and L5-S1 levels ($r=-0.505$, $p<0.001$). These findings indicate that lower SI values were associated with greater degeneration severity at both lower lumbar levels. The correlation of SI with PI and LL were statistically insignificant ($p=0.134$ and $p=0.090$, respectively).

In contrast with SI, STA showed a very strong negative correlation with PI ($r=-0.844$, $p<0.001$). It was negatively correlated with PT ($r=-0.641$, $p<0.001$) and SS ($r=-0.634$, $p<0.001$). There was a positive correlation between LLDI and STA ($r=0.606$, $p<0.001$). Similar to SI, STA showed a strong correlation with L4-5 ($r=-0.771$, $p<0.001$) and L5-S1 ($r=-0.791$, $p<0.001$) Pfirrmann grade. These results suggest that lower STA values were associated with higher Pfirrmann grades at both L4-L5 and L5-S1.

At the L4-L5 level, patients with disc degeneration were significantly older than those without degeneration (49.68 ± 9.49 vs. 45.26 ± 9.79 years, $p=0.032$). The degenerated group had significantly higher PI, PT, and SS values, whereas LLDI, SI, and STA were significantly lower. LL did not differ significantly between the groups ($p=0.279$). At the L5-S1 level, patients with degeneration were also significantly older than those without degeneration (50.72 ± 9.50 vs. 43.81 ± 9.00 years, $p<0.001$). PI, PT, and SS were significantly higher in the degenerated group, while LLDI, SI, and STA were significantly lower. Similar to L4-L5, LL was not significantly different between degenerated and non-degenerated discs ($p=0.244$). In the degeneration pattern analysis, STA showed a stepwise decrease according to the extent of lower lumbar disc degeneration. Mean STA was $105.09 \pm 3.09^\circ$ in patients without degeneration, $101.05 \pm 3.18^\circ$ in isolated L4-L5 degeneration, $99.31 \pm 4.51^\circ$ in isolated L5-S1 degeneration, and $95.85 \pm 4.17^\circ$ in concomitant L4-L5/L5-S1 degeneration (overall $p<0.001$). Although the group means were progressively lower across these categories, the isolated L4-L5 ($n=6$) and isolated L5-S1 ($n=9$) subgroups were small; therefore, these subgroup estimates should be considered exploratory.

To further evaluate the relationship between sacral morphology

Table 1. Distribution of lower lumbar disc degeneration patterns

Degeneration pattern	Number of patients	Percent
No degeneration	37	41.1%
L4-L5 degeneration only	6	6.7%
L5-S1 degeneration only	9	10.0%
Two-levels degeneration	38	42.2%

Table 2. Comparison of demographic and radiographic parameters according to L4-L5 disc degeneration status

Parameters	Non-degenerative	Degenerative	p-value
Age	45.26 ± 9.79	49.68 ± 9.49	0.032
PI	46.26 ± 5.51	53.67 ± 5.43	<0.001
PT	13.69 ± 3.42	17.97 ± 2.90	<0.001
SS	32.57 ± 4.88	35.70 ± 4.47	0.002
LL	50.43 ± 4.81	49.31 ± 4.98	0.279
LLDI	67.13 ± 3.18	61.82 ± 3.60	<0.001
SI	46.53 ± 4.16	42.26 ± 3.91	<0.001
STA	103.96 ± 4.08	96.56 ± 4.40	<0.001

PI: Pelvic incidence, PT: Pelvic tilt, SS: Sacral slope, LL: Lumbar lordosis, LLDI: Lumbar lordosis distribution index, SI: Sacral inclination, STA: Sacral table angle

and the extent of lower lumbar degeneration, patients were grouped according to degeneration burden as no degeneration, single-level degeneration, and two-level degeneration. Mean STA was progressively lower across these groups: $105.09 \pm 3.09^\circ$ in patients without degeneration, $100.01 \pm 4.00^\circ$ in those with single-level degeneration, and $95.85 \pm 4.17^\circ$ in those with two-level degeneration (overall $p < 0.001$). A similar but less pronounced pattern was observed for SI, with corresponding values of $46.71 \pm 4.02^\circ$, $45.13 \pm 4.20^\circ$, and $41.97 \pm 3.98^\circ$ (overall $p < 0.001$) (Table 4). These overall comparisons indicate an association with degeneration burden but do not establish a temporal or causal sequence.

DISCUSSION

The present study evaluated the relationship between sacral morphological parameters and lower lumbar intervertebral disc degeneration at the L4-L5 and L5-S1 levels. The principal finding of this study was that lower STA values were strongly associated with both the presence and severity of lower lumbar disc degeneration. This relationship was observed at both disc levels and became more evident when degeneration was evaluated according to the number of affected levels. Although SI was also significantly associated with degeneration severity, STA demonstrated a stronger and more consistent relationship with Pfirrmann grade and degeneration burden. The progressively lower group means should not, however, be interpreted as proof of a biological sequence, particularly because the isolated L4-L5 and L5-S1 subgroups were small. Numerous studies have investigated the relationship between spinopelvic parameters and lumbar disc degeneration. Ergün

et al.⁽¹⁰⁾ demonstrated that lumbar disc degeneration and disc herniation were inversely correlated with sacral kyphosis and LL angles, emphasizing the importance of sagittal alignment in the development of degenerative lumbar disease. Similarly, Barrey et al.⁽¹¹⁾ reported that patients with lumbar disc herniation frequently exhibit reduced LL and SS compared with healthy individuals, further supporting the role of sagittal spinopelvic imbalance in lumbar degeneration.

Lumbosacral disc degeneration has been shown to closely parallel alterations in lumbosacral stability. In a series of 126 patients, Ohmori⁽¹²⁾ evaluated disc degeneration and intervertebral disc height and demonstrated that progressive degenerative changes significantly influence lumbosacral stability. Likewise, Iguchi et al.⁽¹³⁾ reported that grade III disc degeneration represents a critical threshold for the development of degenerative L4-L5 spondylolisthesis, highlighting the close relationship between disc degeneration and spinal instability. Changes in spinopelvic morphology have also been associated with degenerative lumbar disorders. Mardare et al.⁽¹⁴⁾ observed decreased PI, SS, and LL, accompanied by increased PT, in patients with lumbar degenerative disc disease. Similarly, Oh and Eun⁽¹⁵⁾ demonstrated a significant association between segmental lumbar disc degeneration and both vertebral slip and the lumbosacral angle. In contrast to these findings, our study demonstrated that total LL did not differ significantly between degenerated and non-degenerated groups at either L4-L5 or L5-S1. This suggests that the presence of lower lumbar degeneration may not necessarily be reflected by a reduction in global LL. In contrast, the LLDI was significantly lower in patients with degeneration at both levels. This finding indicates that the distribution of lordosis, rather than the absolute amount of total lordosis, may be more relevant when evaluating lower lumbar disc degeneration. In other words, patients may preserve a similar total LL while demonstrating an unfavorable redistribution of lordosis across the lower lumbar segments. Yang et al.⁽¹⁶⁾ further emphasized the importance of PI in the pathogenesis of lumbar degeneration by demonstrating a significant relationship between increased PI and degenerative lumbar disease. Consistent with these observations, Wang et al.⁽⁵⁾ reported that both PI and STA contribute to the development of L5-S1 spondylolisthesis, underscoring the biomechanical importance of sacropelvic morphology.

The effect of the STA on lumbar degeneration may extend beyond a simple angular measurement. Variations in STA alter the anatomical orientation of the sacral endplate and consequently modify the distribution of mechanical forces acting across the

Table 3. Comparison of demographic and radiographic parameters according to L5-S1 disc degeneration status

Parameters	Non-degenerative	Degenerative	p-value
Age	43.81±9.00	50.72±9.50	<0.001
PI	45.44±4.67	53.94±5.37	<0.001
PT	13.62±3.25	17.75±3.20	<0.001
SS	31.82±4.32	36.19±4.51	<0.001
LL	50.51±4.68	49.31±5.07	0.244
LLDI	67.25±3.16	62.05±3.68	<0.001
SI	46.35±3.97	42.70±4.38	<0.001
STA	104.53±3.38	96.51±4.40	<0.001

PI: Pelvic incidence, PT: Pelvic tilt, SS: Sacral slope, LL: Lumbar lordosis, LLDI: Lumbar lordosis distribution index, SI: Sacral inclination, STA: Sacral table angle

Table 4. Sacral morphological parameters according to the number of degenerated disc levels

Parameter	No degeneration (n=37)	Single-level degeneration (n=15)	Two-level degeneration (n=38)	p-value
SI	46.71±4.02	45.13±4.20	41.97±3.98	<0.001
STA	105.09±3.09	100.01±4.00	95.85±4.17	<0.001

SI: Sacral inclination, STA: Sacral table angle

lumbosacral junction. A lower STA alters the orientation of the sacral endplate and may increase anterior shear forces relative to compressive forces at the lumbosacral junction. Repetitive shear loading may increase stress on the disc and adjacent supporting structures, accelerating degeneration at L5-S1 and, through altered load distribution, at L4-L5. This mechanism may explain the association of lower STA with lower LLDI and multilevel degeneration despite similar total LL. However, this biomechanical explanation remains hypothetical and was not directly evaluated in this study. Although numerous studies have reported that reduced STA is associated with spondylolysis and spondylolisthesis (5), Tallarico et al.⁽³⁾ did not identify a significant association between STA and these pathological conditions, suggesting that the biomechanical role of STA may be more complex than previously assumed. Further evidence supporting the importance of sacral morphology was provided by Strube et al.⁽¹⁷⁾, who identified STA and pelvic radius as the anatomical parameters most strongly associated with lumbar disc degeneration and spinopelvic morphology. These findings are consistent with the present study, in which STA showed the strongest association with lower lumbar disc degeneration among all evaluated radiographic parameters.

Lumbosacral morphology also appears to influence degeneration of the posterior spinal elements. Sahin et al.⁽¹⁸⁾ demonstrated that reduced SS, altered sacral kyphosis, and decreased LL were significantly associated with lumbar facet joint degeneration, indicating that sagittal alignment affects both the intervertebral discs and posterior column structures. Furthermore, the Roussouly classification emphasizes the fundamental role of pelvic morphology in determining sagittal spinal alignment by categorizing both healthy individuals and patients into distinct sagittal alignment profiles⁽¹⁹⁾.

More recently, increasing attention has focused on the contribution of STA to degenerative spinal disease. Khodair et al.⁽²⁰⁾ demonstrated that increased STA combined with reduced sacral kyphosis may accelerate the progression of lumbar degenerative changes. Conversely, decreased STA has been associated with progression of L5 spondylolisthesis, further highlighting the critical biomechanical role of sacral morphology in disorders affecting the lumbosacral junction⁽³⁾. These conflicting results suggest that the role of STA may be dependent on the etiology of the degeneration, such as disc degeneration, spondylolysis, spondylolisthesis or global sagittal morphology. Our findings expand upon these previous observations by demonstrating that STA is strongly associated with degeneration at both the L4-L5 and L5-S1 levels, suggesting that this anatomical parameter may serve as a valuable radiographic marker for identifying individuals at increased risk of lower lumbar degenerative disc disease.

Study Limitations

This study has several limitations. First, its retrospective and cross-sectional design prevents any causal inference

regarding the relationship between sacral morphology and disc degeneration. Second, although the total cohort size was sufficient for the main analyses, the isolated L4-L5 and isolated L5-S1 degeneration subgroups were relatively small; therefore, the pattern-based analysis should be interpreted cautiously. Third, the study population consisted of symptomatic patients presenting with low back pain with or without radicular symptoms, and the findings may not be generalizable to asymptomatic individuals. Finally, clinical outcome measures and longitudinal imaging follow-up were not included, which limits the ability to determine whether STA predicts future degeneration progression. Despite these limitations, this study provides a focused evaluation of sacral morphology in relation to lower lumbar disc degeneration. The findings suggest that STA may be an important morphological marker associated with degeneration at both L4-L5 and L5-S1. More importantly, the stepwise decrease in STA with increasing degeneration burden supports the idea that sacral morphology may be related not only to the severity of degeneration at individual disc levels, but also to the extent of lower lumbar disc involvement. Future prospective studies with larger cohorts and longitudinal follow-up are needed to determine whether STA has predictive value for the development or progression of lower lumbar disc degeneration.

CONCLUSION

This study demonstrates a strong association between sacral morphology and lower lumbar disc degeneration. Lower STA values were associated with higher Pfirrmann grades in both L4-L5 and L5-S1 intervertebral disc levels and with a greater number of degenerated lower lumbar levels. SI was also associated with disc degeneration, however, the association with STA was stronger when degeneration severity and the number of degenerated disc levels were considered. Degenerative changes were observed with higher PI, PT and SS, along with a worse LL distribution pattern. STA may therefore be a useful morphological parameter reflecting the biomechanical environment of the lumbosacral junction. Because the study was cross-sectional and included only symptomatic patients, these findings should not be interpreted as evidence that lower STA causes degeneration or predicts its progression. Longitudinal studies are needed to determine the temporal and predictive role of STA in lower lumbar disc degeneration.

Ethics

Ethics Committee Approval: The ethical approval for this study was obtained from University of Health Sciences Türkiye, Ümraniye Training and Research Hospital Ethical Committee (approval no: 318, date: 23.10.2025).

Informed Consent: Informed consent was obtained from patients.

Footnotes

Authorship Contributions

Surgical and Medical Practices: L.A., B.S., A.T., F.B.Ö., A.F.R., Concept: L.A., B.S., A.T., Design: L.A., B.S., F.B.Ö., A.F.R., Data Collection or Processing: B.S., Analysis or Interpretation: B.S., Literature Search: L.A., A.T., Writing: L.A.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study received no financial support.

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SLEEP QUALITY AND CERVICAL ALIGNMENT IN CHRONIC NECK PAIN

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ABSTRACT

Objective: Sleep impairment frequently accompanies chronic neck pain, but its relationship with cervical sagittal radiographic morphology remains unclear. To investigate associations between sleep quality, neck-specific disability, and cervical sagittal alignment in adults with chronic neck pain.

Materials and Methods: This retrospective cross-sectional study included 86 adults evaluated at a single institution for neck pain lasting at least 6 months. Sleep quality and functional disability were assessed using the Pittsburgh sleep quality index (PSQI) and neck disability index (NDI), respectively. A PSQI score above 5 was defined as poor sleep quality. Lateral cervical radiographs were used to measure C2-C7 lordosis, C7 slope, T1 slope, and T1 slope-C2-C7 Cobb angle (T1S-CL mismatch). Analyses included group comparisons, Spearman correlation, univariable logistic regression, multivariable logistic regression, and multivariable linear regression.

Results: Forty-five patients (52.3%) had poor sleep quality. They had a smaller median C2-C7 lordosis and a higher median NDI score compared with patients with good sleep quality. Higher PSQI scores correlated with lower C2-C7 lordosis and higher C7 slope, T1S-CL mismatch, NDI score, and symptom duration. In multivariable linear regression, NDI remained positively associated with PSQI after adjustment. No evaluated variable remained independently associated with poor sleep quality in the multivariable logistic regression model.

Conclusion: Poor sleep quality was associated with greater neck-related disability and reduced cervical lordosis in adults with chronic neck pain. Joint assessment of sleep quality, disability, and cervical sagittal alignment may enable broader clinical characterization. These findings should be interpreted cautiously because the study was cross-sectional.

Keywords: Chronic neck pain, sleep disturbance, cervical sagittal alignment, Pittsburgh sleep quality index, Neck disability index

INTRODUCTION

Chronic neck pain may interfere with daily activities, emotional well-being, and occupational functioning, extending its impact beyond the presence of pain alone. Sleep problems are frequently encountered in this patient population and are also associated with greater clinical burden. Evidence from experimental and longitudinal research indicates that sleep impairment and pain may influence each other; however, the mechanisms and relative importance of these reciprocal effects remain uncertain⁽¹⁾. Studies focusing specifically on individuals with neck pain have linked poorer sleep with greater neck-related disability and prolonged symptoms⁽²⁻⁴⁾.

Several mechanisms may account for the relationship between disturbed sleep and persistent neck symptoms. Experimental evidence has linked inadequate sleep with heightened nociceptive processing, reduced endogenous pain control, greater

fatigue, and greater perceived functional limitation. Conversely, ongoing neck pain has been associated with difficulties in sleep onset and continuity, supporting a potentially bidirectional relationship between sleep impairment and pain. Evidence from a cotwin analysis indicates that shared hereditary influences may partly contribute to this relationship, suggesting that it cannot be attributed exclusively to mechanical, behavioral, or lifestyle-related factors⁽²⁾. Nevertheless, previous investigations have concentrated mainly on symptom severity, psychosocial characteristics, and functional disability, whereas the possible role of cervical sagittal morphology has been examined far less extensively.

Radiographic assessment of cervical sagittal balance is increasingly used to characterize cervical spine disorders. The principal measurements include C2-C7 lordosis, C7 slope, T1 slope, and the T1 slope-C2-C7 Cobb angle (T1S-CL mismatch)^(5,6). Together, these variables describe the orientation of the cervicothoracic junction and the degree to which cervical curvature accommodates

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Received: 10.07.2026 **Accepted:** 15.08.2026 **Publication Date:** 14.10.2026

Cite this article as: Bulut M, Seyfettinoğlu F. Sleep quality and cervical alignment in chronic neck pain. J Turk Spinal Surg. 2026;37(4):148-154



the underlying sagittal profile. Because a greater T1 slope generally requires a corresponding increase in cervical lordosis to preserve forward gaze, an excessive T1S-CL mismatch may indicate inadequate compensatory curvature⁽⁷⁾. Clinical studies have further reported relationships between disturbed cervical alignment, axial neck symptoms, degenerative changes, and worse patient-reported function⁽⁸⁻¹²⁾.

Although sleep disturbance and cervical sagittal alignment have each been studied in relation to neck pain, their relationship within the same patient population remains poorly characterized. Determining whether sleep impairment accompanies specific radiographic patterns, in addition to greater functional limitation, could improve the clinical phenotyping of chronic neck pain. Such an approach is relevant because sleep represents a potentially modifiable component of the condition, whereas sagittal measurements may provide objective information about cervical mechanical configuration. This study investigated whether sleep quality was related to neck-specific disability and sagittal cervical radiographic measurements in adults with chronic neck pain. We expected poorer sleep quality to accompany greater disability and less favorable sagittal alignment, with reduced C2-C7 lordosis considered the primary radiographic pattern of interest.

MATERIALS AND METHODS

Study Design and Setting

This retrospective cross-sectional investigation was conducted at a single orthopedic outpatient center. The source population comprised adults evaluated for neck pain persisting for at least 6 months between January 2024 and December 2025. Records were screened for the concurrent availability of clinical information, completed Pittsburgh sleep quality index (PSQI) and neck disability index (NDI) questionnaires, and technically adequate lateral cervical radiographs. Data obtained during the corresponding clinical assessment were extracted and evaluated at a single time point. Accordingly, the analyses were intended to evaluate associations among variables and not to establish temporal or causal relationships.

The study protocol was approved by the Scientific Research Ethics Committee of University of Health Sciences Türkiye, Adana City Training and Research Hospital (approval no: 1499, date: 25.06.2026). The research procedures conformed to the Declaration of Helsinki, and the dataset was de-identified before statistical analysis. Patient data were analyzed after anonymization. The requirement for written informed consent was handled in accordance with the decision of the ethics committee.

Study Population

Patients were eligible when they were adults with neck pain of at least 6 months' duration and had complete PSQI, NDI, clinical, and lateral cervical radiographic records from the same assessment period. Radiographs were required to permit

reliable measurement of the prespecified sagittal parameters. Records were not considered when patients had undergone previous cervical spine surgery or had a history of cervical trauma, spinal infection, neoplastic disease, inflammatory rheumatic disease, congenital cervical deformity, or a major neurologic deficit. Images with inadequate visualization or technical quality for sagittal measurement were also excluded. Each individual contributed only one record to the analytical cohort. The variables used in the final analyses were complete for all included patients.

Clinical and Questionnaire-based Assessment

Age, sex, and symptom duration were obtained from the clinical records. Previous management was recorded under four categories: medical treatment, physical therapy, lifestyle modification, and exercise participation. Symptom duration was expressed in months.

Sleep status was quantified with the PSQI, which provides a global score from 0 to 21 for sleep during the previous month. Increasing scores represent progressively poorer sleep. The global PSQI score was retained as a continuous variable for correlation and linear regression analyses to preserve the full range of sleep quality information. For categorical analyses, the established PSQI cut-off of >5 was used to distinguish poor from good sleep quality, allowing clinically interpretable group comparisons and logistic regression analyses.

Neck-specific functional limitation was measured with the NDI. The total NDI score was evaluated continuously in the main statistical analyses. For descriptive presentation, scores were grouped as no disability (0-4), mild disability (5-14), moderate disability (15-24), severe disability (25-34), or complete disability (35-50)^(13,14). A separate standardized measure of pain intensity, such as a visual analog scale or numerical rating scale, was not consistently available in the retrospective records for the corresponding assessment period and therefore could not be included in the analyses. Standardized psychological assessments for symptoms such as anxiety and depression were not routinely available in the retrospective records and therefore could not be included in the analyses.

Radiographic Assessment

Sagittal measurements were obtained from lateral cervical radiographs. The radiographic variables comprised C2-C7 lordosis, C7 slope, T1 slope, and T1S-CL mismatch.

C2-C7 lordosis was determined from the angle formed by lines drawn along the inferior endplates of C2 and C7. T1 slope was defined by the inclination of the superior T1 endplate relative to a horizontal line. The corresponding inclination of the superior C7 endplate was recorded as C7 slope. T1S-CL mismatch was derived for each patient as follows:

T1S-CL mismatch=T1 slope-C2-C7 Cobb angle

All measurements were expressed in degrees. Agreement between observers was examined using an intraclass correlation coefficient (ICC) derived from a two-way random-effects,

absolute-agreement model. The resulting ICC is presented with the study findings.

Outcomes

The primary outcome was poor sleep quality, defined as PSQI >5. Secondary analyses evaluated the PSQI score as a continuous outcome. The main explanatory variables were cervical sagittal radiographic parameters, NDI score, symptom duration, age, sex, and treatment-related variables.

Statistical Analysis

Statistical analyses were conducted using R version 4.6.1. Continuous data are reported as medians with interquartile ranges (IQRs) because the principal clinical and questionnaire scores did not follow a normal distribution or were ordinal in nature. Categorical data are summarized as numbers and percentages.

For the between-group analyses, patients were divided according to PSQI-defined sleep status. Continuous variables were examined with the Mann-Whitney U test, while categorical variables were assessed with Fisher's exact test.

Relationships between the continuous PSQI score and clinical or radiographic measurements were evaluated using Spearman's rank correlation coefficient. The same correlation method was applied separately to investigate the associations between NDI scores and cervical sagittal measurements.

Separate univariable logistic regression models were fitted with poor sleep quality as the binary dependent variable. Effect estimates are presented as odds ratios (ORs) with 95% confidence intervals. The multivariable logistic regression model incorporated age, sex, T1S-CL mismatch, NDI score, and symptom duration. Covariate selection was determined a priori according to clinical relevance, the need to limit the number of predictors relative to the available sample size, and the need to avoid redundancy among closely related sagittal alignment parameters. Because T1S-CL mismatch was calculated from T1 slope and C2-C7 Cobb angle, T1 slope, C2-C7 Cobb angle, and T1S-CL mismatch were not entered simultaneously into the same multivariable model. T1S-CL mismatch was selected as a composite sagittal parameter to represent the relationship between cervicothoracic inclination and cervical lordosis while avoiding simultaneous inclusion of mathematically dependent sagittal variables.

A multivariable linear regression model was also constructed with the total PSQI score as the dependent variable. Age, sex, T1S-CL mismatch, NDI score, and symptom duration were entered simultaneously as covariates. Model estimates are presented as unstandardized regression coefficients with their standard errors (SEs). Variance inflation factors (VIFs) were examined to evaluate multicollinearity among variables included in the final multivariable model, and VIF values >5 were considered suggestive of relevant multicollinearity.

All analyses were two-tailed, and statistical significance was defined as $p < 0.05$.

RESULTS

The final cohort comprised 86 patients, with complete clinical and radiographic data available for all evaluated variables. The median age was 54.00 years (IQR, 51.25-58.00), and 54 patients (62.8%) were female. The median PSQI score was 6.00 (IQR, 4.00-6.00), and 45 patients (52.3%) were classified as having poor sleep quality. According to NDI classification, 47 patients (54.7%) had mild disability and 39 patients (45.3%) had moderate disability (Table 1).

When patients were compared according to sleep quality, the poor sleep quality group had a lower median C2-C7 lordosis than the good sleep quality group [9.00 (IQR, 5.00-13.90) vs. 25.30 (IQR, 6.00-30.30), $p = 0.003$]. T1 slope distribution differed between groups ($p = 0.035$). The poor sleep quality group had higher NDI scores than the good sleep quality group [16.00 (IQR, 10.00-18.00) vs. 12.00 (IQR, 10.00-16.00), $p = 0.040$]. Exercise participation was more frequent in the poor sleep quality group (64.4% vs. 26.8%, $p < 0.001$). Age, sex, C7 slope, T1S-CL mismatch, symptom duration, medical treatment, physical therapy, and lifestyle change did not differ significantly between sleep quality groups (Table 2). The interobserver reliability of radiographic measurements was good, with an ICC of 0.83.

Spearman correlation analysis showed that PSQI score was negatively correlated with C2-C7 lordosis ($\rho = -0.219$, $p = 0.043$) and positively correlated with C7 slope ($\rho = 0.242$, $p = 0.025$), T1S-CL mismatch ($\rho = 0.220$, $p = 0.042$), NDI score ($\rho = 0.436$,

Table 1. Baseline characteristics of the study cohort

Variable	Overall cohort, n=86
Age, years	54.00 (51.25-58.00)
Female sex	54 (62.8%)
Male sex	32 (37.2%)
C2-C7 lordosis, (°)	11.00 (5.12-26.75)
C7 slope, (°)	27.00 (24.00-33.00)
T1 slope, (°)	24.50 (21.50-28.00)
T1S-CL mismatch, (°)	11.00 (-2.05-19.06)
NDI score	13.00 (10.00-17.00)
PSQI score	6.00 (4.00-6.00)
Symptom duration, months	12.00 (10.00-14.00)
Medical treatment	55 (64.0%)
Physical therapy	17 (19.8%)
Lifestyle change	48 (55.8%)
Exercise	40 (46.5%)
Good sleep quality	41 (47.7%)
Poor sleep quality	45 (52.3%)
Mild disability	47 (54.7%)
Moderate disability	39 (45.3%)

Values are presented as median (interquartile range) or n (%). NDI: Neck disability index, PSQI: Pittsburgh sleep quality index, T1S-CL mismatch: T1 slope-C2-C7 Cobb angle

$p < 0.001$), and symptom duration ($\rho = 0.270$, $p = 0.012$). No significant correlations were observed between PSQI score and age or T1 slope (Table 3).

NDI score showed significant correlations with all evaluated radiographic parameters. It was negatively correlated with C2-C7 lordosis ($\rho = -0.409$, $p < 0.001$) and positively correlated with C7 slope ($\rho = 0.526$, $p < 0.001$), T1 slope ($\rho = 0.651$, $p < 0.001$), and T1S-CL mismatch ($\rho = 0.759$, $p < 0.001$) (Supplementary Table 1).

In univariable logistic regression analysis, C2-C7 lordosis (OR=0.924, 95% CI: 0.884-0.965, $p < 0.001$), T1 slope (OR=0.918, 95% CI: 0.867-0.972, $p = 0.003$), NDI score (OR=1.111, 95% CI: 1.001-1.234, $p = 0.048$), and exercise participation (OR=4.943, 95% CI: 1.966-12.427, $p < 0.001$) were associated with poor sleep quality. Male sex showed a borderline association with poor sleep quality but did not reach statistical significance (OR=2.386, 95% CI: 0.965-5.903, $p = 0.060$). Physical therapy was not significantly associated with poor sleep quality in the univariable analysis (OR=2.618, 95% CI: 0.833-8.229, $p = 0.100$) (Supplementary Table 2).

In the multivariable logistic regression model including age, sex, T1S-CL mismatch, NDI score, and symptom duration, none of the variables remained independently associated with poor sleep quality (Table 4). When PSQI score was analyzed as a continuous outcome using multivariable linear regression, NDI score remained positively associated with PSQI score after adjustment ($\beta = 0.255$, SE=0.058, $p < 0.001$). T1S-CL mismatch showed a negative association with PSQI score after adjustment ($\beta = -0.047$, SE=0.018, $p = 0.009$). The overall model was statistically significant (adjusted $R^2 = 0.216$, $F = 5.681$, $p < 0.001$). VIF values for the multivariable linear regression model were 1.178 for age, 1.181 for male sex, 2.430 for T1S-CL mismatch, 3.060 for NDI score, and 1.789 for symptom duration. All VIF values were below 5, indicating no severe multicollinearity in the final model (Table 5).

DISCUSSION

The main observation in this cohort was that poorer sleep accompanied greater neck-related disability and reduced C2-

Table 2. Comparison of patients according to sleep quality

Variable	Good sleep quality, n=41	Poor sleep quality, n=45	p-value
Age, years	53.00 (52.00-55.00)	54.00 (51.00-59.00)	0.193
C2-C7 lordosis, (°)	25.30 (6.00-30.30)	9.00 (5.00-13.90)	0.003
C7 slope, (°)	26.00 (23.70-33.00)	27.00 (25.00-33.00)	0.762
T1 slope, (°)	24.00 (21.50-33.00)	26.00 (12.80-26.00)	0.035
T1S-CL mismatch, (°)	7.00 (-1.00-19.00)	14.00 (-2.20-21.00)	0.326
NDI score	12.00 (10.00-16.00)	16.00 (10.00-18.00)	0.040
Symptom duration, months	12.00 (10.00-13.00)	12.00 (10.00-14.00)	0.232
Female sex	30 (73.2%)	24 (53.3%)	0.075
Male sex	11 (26.8%)	21 (46.7%)	
Medical treatment	25 (61.0%)	30 (66.7%)	0.656
Physical therapy	5 (12.2%)	12 (26.7%)	0.110
Lifestyle change	20 (48.8%)	28 (62.2%)	0.278
Exercise	11 (26.8%)	29 (64.4%)	<0.001

Values are presented as median (interquartile range) or n (%). Continuous variables were compared using the Mann-Whitney U test. Categorical variables were compared using Fisher's exact test. PSQI score was not compared between groups because sleep quality grouping was defined according to PSQI. NDI: Neck disability index, PSQI: Pittsburgh sleep quality index, T1S-CL mismatch: T1 slope-C2-C7 Cobb angle

Table 3. Correlations between PSQI score and clinical/radiographic parameters

Variable	Spearman's rho	p-value
Age, years	0.077	0.481
C2-C7 lordosis, (°)	-0.219	0.043
C7 slope, (°)	0.242	0.025
T1 slope, (°)	0.079	0.471
T1S-CL mismatch, (°)	0.220	0.042
NDI score	0.436	<0.001
Symptom duration, months	0.270	0.012

NDI: Neck disability index, PSQI: Pittsburgh sleep quality index, T1S-CL mismatch: T1 slope-C2-C7 Cobb angle

Table 4. Multivariable logistic regression analysis for poor sleep quality

Variable	OR	95% CI	p-value
Age	1.026	0.976-1.078	0.316
Male sex	1.824	0.679-4.901	0.234
T1S-CL mismatch	0.985	0.932-1.040	0.584
NDI score	1.140	0.949-1.369	0.162
Symptom duration	0.961	0.780-1.184	0.709

ORs for continuous variables are reported per 1-unit increase. OR: Odds ratio, CI: Confidence interval, NDI: Neck disability index, T1S-CL mismatch: T1 slope-C2-C7 Cobb angle

Table 5. Multivariable linear regression analysis for PSQI score

Variable	β	SE	t-value	p-value	VIF
Age	-0.002	0.016	-0.116	0.908	1.178
Male sex	0.031	0.319	0.098	0.922	1.181
T1S-CL mismatch	-0.047	0.018	-2.664	0.009	2.430
NDI score	0.255	0.058	4.377	<0.001	3.060
Symptom duration	0.006	0.067	0.096	0.924	1.789

Model statistics: adjusted $R^2=0.216$; $F=5.681$; $p<0.001$. β values are unstandardized regression coefficients from the multivariable linear regression model. NDI: Neck disability index, PSQI: Pittsburgh sleep quality index, T1S-CL mismatch: T1 slope-C2-C7 Cobb angle, SE: Standard error, VIF: Variance inflation factor

C7 lordosis, with PSQI scores also showing relationships with several cervical sagittal measurements. By examining sleep status, patient-reported disability, and cervical alignment within the same cohort, the present analysis provides a combined clinical and radiographic perspective on chronic neck pain.

In the present cohort, 52.3% of patients were classified as having poor sleep quality. Patients with poor sleep quality had significantly lower C2-C7 Cobb angles and higher NDI scores compared with those with good sleep quality. PSQI score also showed a moderate positive correlation with NDI score. This pattern accords with earlier studies linking impaired sleep to greater pain-related functional limitation^(1-4,15). Finan et al.⁽¹⁾ described reciprocal interactions between sleep and pain, including increased nociceptive sensitivity and reduced pain-regulatory capacity following inadequate sleep. Similarly, Andreucci et al.⁽²⁾ reported an association between sleep quality and chronic neck pain in a cotwin design, although their findings also suggested that this relationship may be partly influenced by shared genetic factors. Accordingly, the observed relationships do not establish that sleep impairment causes radiographic alterations or disability; rather, they indicate associations between sleep status and the clinical characteristics of chronic neck pain.

The association between poor sleep quality and chronic neck pain has also been reported in longitudinal and cross-sectional clinical studies^(3,4,16). Yabe et al.⁽³⁾ showed that sleep disturbance was associated with neck pain over a 3-year follow-up period, supporting the potential role of sleep disturbance in symptom persistence. Lee and Oh⁽⁴⁾ also demonstrated that sleep quality was related to neck pain, shoulder pain, disability, physical activity, and perceived health in middle-aged women. In addition, longitudinal population-based data

have suggested that insomnia is associated with an increased risk of chronic musculoskeletal complaints, including neck-related complaints⁽¹⁶⁾. In line with these studies, our results showed that worse PSQI scores were associated with higher NDI scores. Importantly, NDI remained positively associated with PSQI score after adjustment in the multivariable linear regression model. This suggests that neck-related disability is an important clinical correlate of sleep quality in patients with chronic neck pain. The categorical and continuous PSQI analyses should be regarded as complementary rather than interchangeable, because dichotomization at a clinical cut-off reduces within-group information, whereas continuous analysis retains variation across the full PSQI range. Accordingly, the absence of independently significant predictors in the multivariable logistic regression model does not necessarily contradict the associations identified in the linear regression model. The two models evaluate different representations of sleep quality and may differ in statistical sensitivity, particularly in a modest-sized cohort.

Radiographically, patients with poor sleep quality demonstrated a smaller C2-C7 lordosis than those with good sleep quality. Cervical sagittal configuration can be characterized using measurements such as C2-C7 lordosis, T1 slope, C7 slope, and T1S-CL mismatch, each of which reflects a different component of cervicothoracic balance^(5,6). Reduced cervical lordosis may reflect altered sagittal mechanics, compensatory muscle activity, or pain-related postural adaptation. Earlier clinical studies have reported that deviations in cervical sagittal alignment may accompany axial symptoms and poorer patient-reported function^(8,9,11,12). Our findings are broadly consistent with this literature, as lower lordosis was observed in patients with poor sleep quality and was negatively correlated with both

PSQI and NDI scores. Although the between-group difference in C2-C7 lordosis was statistically significant, the correlation between continuous PSQI score and C2-C7 lordosis was weak ($\rho = -0.219$). These findings are not necessarily contradictory because the between-group analysis evaluates differences in lordosis distributions across the PSQI-defined cut-off, whereas Spearman correlation evaluates the monotonic relationship across the full range of PSQI scores. The modest correlation may also reflect the limited dispersion of PSQI scores and the within-group variability in cervical lordosis. Therefore, the association between PSQI and cervical lordosis should be interpreted as statistically significant but weak in magnitude. The cross-sectional design does not permit determination of whether diminished lordosis precedes sleep impairment, whether pain and disturbed sleep alter posture or muscular activity, or whether these findings arise from a common underlying process.

The relationship between T1 slope, cervical lordosis, and clinical symptoms requires careful interpretation. T1 slope is biomechanically related to cervical lordosis, and higher T1 slope generally requires greater cervical lordosis to maintain horizontal gaze and sagittal balance⁽⁷⁾. In our study, T1 slope distribution differed between sleep quality groups and was associated with poor sleep quality in univariable logistic regression. However, T1 slope was not significantly correlated with PSQI score. Moreover, T1 slope, C2-C7 lordosis, and T1S-CL mismatch are closely related sagittal alignment parameters, and T1S-CL mismatch is mathematically derived from T1 slope and C2-C7 Cobb angle. Therefore, these parameters were not entered simultaneously into the multivariable models. T1S-CL mismatch was retained as the representative composite sagittal parameter to avoid redundant modeling of overlapping sagittal constructs. Accordingly, the T1 slope finding should be interpreted as exploratory rather than definitive.

T1S-CL mismatch also warrants cautious interpretation because it is mathematically derived from T1 slope and C2-C7 lordosis rather than being an independent sagittal measurement. In the unadjusted correlation analysis, T1S-CL mismatch was positively correlated with both PSQI and NDI scores. However, after multivariable adjustment, its association with PSQI changed direction and became negative. This reversal indicates that the adjusted coefficient is dependent on the covariate structure of the model and may reflect shared variance, particularly with NDI, rather than an independent inverse relationship between T1S-CL mismatch and sleep quality. Although T1 slope, C2-C7 lordosis, and T1S-CL mismatch were not entered simultaneously and VIF values did not indicate severe multicollinearity among the variables included in the final model, these findings do not eliminate the mathematical dependence of T1S-CL on its component sagittal measurements. Therefore, the adjusted negative coefficient should be interpreted cautiously and should not be regarded as evidence that greater T1S-CL mismatch is associated with better sleep quality.

The strong correlations observed between NDI and radiographic

parameters further support the clinical relevance of cervical sagittal morphology in chronic neck pain. NDI showed significant associations with C2-C7 Cobb angle, C7 slope, T1 slope, and T1S-CL mismatch. These findings are compatible with prior work showing relationships between cervical sagittal parameters and patient-reported disability, particularly in cervical degenerative or postoperative populations^(9,12). Nevertheless, our cohort differs from many surgical series because it consisted of patients evaluated for chronic neck pain rather than a homogeneous operative population. This may make the findings more relevant to outpatient clinical assessment, but it also increases heterogeneity and limits direct comparison with surgically treated cohorts.

Exercise participation was more frequent in the poor sleep quality group and was associated with poor sleep quality in univariable logistic regression. This result should be interpreted carefully. It should not be concluded that exercise worsens sleep quality. A more plausible explanation is that patients with more severe symptoms, higher disability, or greater health concerns may have been more likely to perform exercise or to be advised to exercise. Lee and Oh⁽⁴⁾ similarly evaluated physical activity within the broader relationship between sleep quality, pain, and disability, supporting the idea that physical activity should be considered as part of a multidimensional clinical context rather than as an isolated causal factor. In addition, population-based evidence suggests that exercise may modify the relationship between sleep problems and chronic musculoskeletal pain rather than represent a simple harmful exposure⁽¹⁵⁾. Because of the cross-sectional design, reverse association and indication bias cannot be excluded.

Study Limitations

Several methodological considerations should be acknowledged. Most importantly, the cross-sectional assessment allows identification of associations but does not establish their temporal sequence, directionality, or causality. No formal a priori sample size calculation was performed because the study was retrospective and the sample size was determined by the number of eligible patients with complete clinical, questionnaire-based, and radiographic data. No post-hoc power analysis was performed. Therefore, although the number of poor sleep quality events was acceptable for the five-covariate logistic regression model according to the commonly used events-per-variable rule of thumb, the adjusted regression analyses may still have been underpowered to detect small independent associations. Exercise participation was more frequent among patients with poor sleep quality; however, this unadjusted association should be interpreted within the limitations of the cross-sectional design. Indication bias is likely, as patients with more severe symptoms, greater disability, or higher health concerns may have been more likely to perform exercise or to be advised to exercise.

An important limitation is the absence of a separate standardized measure of pain intensity. Because pain severity may be

associated with both sleep quality and neck-related disability, its omission introduces the possibility of residual confounding and limits interpretation of the observed associations between sleep quality and cervical sagittal parameters. In addition, standardized psychological assessments were not available. Anxiety, depression, catastrophizing, and psychological distress may be associated with both sleep quality and chronic neck pain; therefore, failure to account for these factors may have resulted in residual confounding^(1,2). Other unmeasured factors, including exercise type and intensity, adherence, medication use, and occupational factors, could not be fully accounted for. Therefore, treatment-related variables were interpreted descriptively and should not be considered evidence of causal effects on sleep quality. In addition, lateral cervical radiographs represent alignment at a single static time point and cannot characterize dynamic postural changes, paraspinal muscle function, or movement adaptations related to pain. Finally, the PSQI reflects overall perceived sleep quality but does not establish the presence of specific sleep disorders such as insomnia, obstructive sleep apnea, or circadian rhythm disorders.

CONCLUSION

In this cross-sectional cohort of patients with chronic neck pain, poor sleep quality was common and was associated with greater neck-related disability and lower C2-C7 lordosis, with additional associations observed between PSQI score and selected cervical sagittal parameters. NDI score remained positively associated with PSQI score after adjustment, whereas no variable remained independently associated with dichotomized poor sleep quality in the multivariable logistic regression model.

These findings suggest that sleep quality, functional disability, and cervical sagittal morphology may represent interrelated components of the chronic neck pain phenotype. However, because of the cross-sectional design, causal or directional relationships cannot be inferred. Future prospective studies with larger cohorts and broader clinical, psychological, and dynamic postural assessments are needed to clarify the mechanisms underlying these associations.

Ethics

Ethics Committee Approval: The study protocol was approved by the Scientific Research Ethics Committee of University of Health Sciences Türkiye, Adana City Training and Research Hospital (approval no: 1499, date: 25.06.2026).

Informed Consent: Patient data were analyzed after anonymization. The requirement for written informed consent was handled in accordance with the decision of the ethics committee.

Footnotes

Authorship Contributions

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

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study received no financial support.

Supplementary Table 1-2 links: <https://d2v96fxpocvxx.cloudfront.net/68ab204c-182b-49da-b227-bc7efe058632/content-images/21adfe98-e216-4330-a219-8bfd04610d46.pdf>

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PRE-INCISIONAL CAUDAL EPIDURAL ANALGESIA VERSUS LOCAL SURGICAL-SITE INFILTRATION FOR EARLY PAIN CONTROL AFTER LUMBAR MICRODISCECTOMY: A RETROSPECTIVE COMPARATIVE COHORT STUDY

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ABSTRACT

Objective: Preemptive analgesia may reduce early postoperative pain after lumbar microdiscectomy, but the optimal anatomical target for local anesthetic delivery remains unclear. This study compared pre-incisional caudal epidural analgesia (pre-CEA) with pre-incisional local surgical-site infiltration (pre-LSSI) for single-level lumbar microdiscectomy.

Materials and Methods: This retrospective comparative cohort study analyzed prospectively recorded perioperative pain data from adults undergoing single-level lumbar microdiscectomy in 2022. Analgesic protocols were not randomized; patients selected pre-LSSI, pre-CEA, or no preemptive analgesia after preoperative discussion. The primary analysis compared pre-LSSI with pre-CEA; the control cohort was exploratory. The primary outcome was the 24-hour visual analog scale (VAS)-back area under the curve (AUC). Secondary outcomes included VAS-leg AUC, rescue analgesia, opioid rescue, ambulation time, length of stay, and adverse events.

Results: The study included 138 patients: 47 pre-LSSI, 42 pre-CEA, and 49 controls. VAS-back AUC was lower with pre-CEA than pre-LSSI (42.2 ± 8.0 vs. 64.0 ± 6.0 ; $p < 0.001$), as was VAS-leg AUC [0.0 ($0.0-0.0$) vs. 8.0 ($8.0-8.0$); $p < 0.001$]. Rescue analgesia was required in all pre-LSSI patients but in none of the pre-CEA patients ($p < 0.001$). Neither active-treatment group required opioid rescue.

Conclusion: Pre-CEA was associated with lower early postoperative pain burden and no rescue analgesic requirement during the first 24 hours compared with pre-LSSI. Given the preference-based, non-randomized design and non-equivalent bupivacaine protocols, prospective, randomized, dose-standardized studies are needed to confirm these findings.

Keywords: Lumbar microdiscectomy, preemptive analgesia, caudal epidural analgesia, local infiltration, postoperative pain

INTRODUCTION

Lumbar microdiscectomy is commonly performed for symptomatic lumbar disc herniation and is generally associated with rapid relief of radicular symptoms. Nevertheless, early postoperative pain remains clinically relevant because it can affect patient comfort, analgesic requirement, mobilization, and discharge readiness. Contemporary procedure-specific pain management recommendations for lumbar posterior decompressive procedures emphasize multimodal analgesia and generally reserve opioids for rescue treatment, reflecting the need for effective opioid-sparing strategies in the early postoperative period⁽¹⁾. In lumbar spine surgery, preemptive analgesia has been evaluated as one such strategy, with meta-analytic evidence suggesting potential reductions in early

postoperative pain and analgesic consumption, although the magnitude of benefit varies according to the analgesic technique and surgical context⁽²⁾.

The rationale for preemptive analgesia is based on the concept that noxious input before and during surgery may contribute to postoperative pain amplification through peripheral and central sensitization. Experimental work by Woolf⁽³⁾ demonstrated that tissue injury can produce a central component of post-injury pain hypersensitivity, providing an important biological basis for strategies aimed at limiting nociceptive input before it becomes established. Kissin⁽⁴⁾ later emphasized that preemptive analgesia should be understood not merely as an intervention given before incision, but as an attempt to reduce postoperative pain by preventing or attenuating sensitization caused by perioperative noxious stimuli. More recent network

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Received: 08.06.2026 **Accepted:** 24.08.2026 **Publication Date:** 14.10.2026

Cite this article as: Çal MA, Yavuz AY. Pre-incisional caudal epidural analgesia versus local surgical-site infiltration for early pain control after lumbar microdiscectomy: a retrospective comparative cohort study. J Turk Spinal Surg. 2026;37(4):155-164



meta-analytic evidence also supports the general concept that preemptive analgesic interventions can improve postoperative pain outcomes, while highlighting heterogeneity across drug classes, routes, and procedures⁽⁵⁾.

Within contemporary enhanced recovery after surgery (ERAS) pathways for spine surgery, multimodal opioid-sparing analgesia and early mobilization are central components of perioperative care⁽⁶⁾. Regional analgesic techniques are increasingly incorporated into these pathways to improve early pain control while limiting systemic opioid exposure. Among newer fascial-plane approaches, erector spinae plane block (ESPB) and thoracolumbar interfascial plane (TLIP) block have accumulated substantial randomized and meta-analytic evidence in lumbar spine surgery⁽⁷⁻⁹⁾. Both techniques have been associated with lower postoperative pain scores and opioid consumption, although comparative evidence remains heterogeneous and no single regional technique has been established as universally optimal⁽⁷⁻⁹⁾. Caudal epidural analgesia represents a different, neuraxial approach that may provide cephalad epidural distribution through a sacral access point and can be performed after prone positioning without altering the operative setup. In adult lumbar spine surgery, however, its contemporary evidence base is smaller than that of ESPB and TLIP, particularly for direct comparisons with simpler surgical-site infiltration protocols.

Within this broader multimodal framework, pre-incisional local surgical-site infiltration (pre-LSSI) and pre-incisional caudal epidural analgesia (pre-CEA) represent two practical but anatomically distinct approaches to pain control in lumbar microdiscectomy. Local surgical-site infiltration targets the skin, subcutaneous tissue, and paraspinal muscle layers and is technically simple, familiar, and widely applicable. However, systematic reviews of local anesthetic wound or paraspinal infiltration in lumbar spine surgery have reported variable and often modest early analgesic effects^(10,11). By contrast, caudal epidural analgesia delivers local anesthetic into the epidural compartment and may provide a broader proximal neural target for early postoperative analgesia. Randomized studies have suggested that preemptive caudal epidural local anesthetic administration can reduce early postoperative pain and analgesic requirement after lumbar disc or lumbosacral spine surgery^(12,13). Despite the availability of studies evaluating these techniques separately, direct comparative evidence between pre-LSSI and pre-CEA in single-level lumbar microdiscectomy remains limited. Clarifying this comparison is clinically relevant because these methods differ not only in technical invasiveness but also in anatomical target, drug distribution, and expected analgesic field. Therefore, this study aimed to compare pre-LSSI with pre-CEA for early postoperative pain control after single-level lumbar microdiscectomy. The primary endpoint was cumulative visual analog scale (VAS)-back pain burden during the first 24 postoperative hours, expressed as area under the curve (AUC). Secondary outcomes included VAS-leg AUC, postoperative VAS trajectories, rescue analgesic requirement, ambulation time,

length of hospital stay, and adverse events. A no preemptive analgesia control cohort was retained as an exploratory contextual comparator.

MATERIALS AND METHODS

Study Design and Ethics

This study was conducted as a retrospective comparative cohort analysis of prospectively recorded standardized perioperative pain data. The study was approved by the University of Health Sciences Türkiye, Prof. Dr. Cemil Taşcıoğlu City Hospital Ethics Committee before data analysis (approval no: 22, date: 23.01.2023) and was conducted in accordance with the principles of the Declaration of Helsinki. Written informed consent for surgery and perioperative analgesic procedures was obtained according to institutional practice.

Consecutive adult patients who underwent single-level lumbar microdiscectomy for lumbar disc herniation during 2022 were screened for eligibility. Patients were classified according to the analgesic approach actually performed before skin incision: pre-LSSI, pre-CEA, or no preemptive analgesia.

The primary analysis focused on the active-treatment comparison between pre-LSSI and pre-CEA. The no preemptive analgesia control cohort was retained only as an exploratory contextual comparator to describe the clinical magnitude of preemptive analgesia relative to no preemptive intervention.

Preemptive analgesic interventions were not assigned by randomization. In routine clinical practice, patients were informed preoperatively about available postoperative pain control options, and the selected pre-incisional analgesic technique was performed when the patient consented to and preferred that approach. Because the analgesic technique was selected according to patient preference after preoperative discussion rather than random allocation, the active-treatment groups may have differed in unmeasured factors such as pain expectations, anxiety, treatment preference, or perceived need for neuraxial analgesia. These potential sources of selection bias were considered when interpreting the results.

Participants

Patients were included if they were 18 years of age or older, had American Society of Anesthesiologists (ASA) physical status I or II, had magnetic resonance imaging-confirmed single-level lumbar disc herniation with radiculopathy, and underwent standard single-level lumbar microdiscectomy.

Patients were excluded if they underwent multilevel surgery, revision surgery, additional decompressive procedures, fusion surgery, or a surgical approach other than standard single-level lumbar microdiscectomy. Patients with ASA physical status III or IV, morbid obesity, known allergy to any study medication, drug or alcohol abuse, chronic narcotic use, or incomplete perioperative pain records were also excluded.

Anesthesia and Surgical Procedure

All procedures were performed under general anesthesia in the prone position using the same institutional anesthetic protocol. General anesthesia was induced with propofol and fentanyl 2 µg/kg, and tracheal intubation was facilitated with atracurium. The induction dose of fentanyl represented the total intraoperative fentanyl exposure; no additional fentanyl or other intraoperative opioid bolus was administered, and remifentanyl infusion was not used. Anesthesia maintenance followed the institutional volatile anesthetic protocol. However, individual volatile anesthetic concentrations and end-tidal minimum alveolar concentration (MAC) values were not systematically available in the retrospective records and therefore could not be reliably analyzed.

A standard posterior lumbar microdiscectomy was performed in all patients. After a midline lumbar skin incision, the thoracolumbar fascia was opened, and the paraspinal muscles were dissected subperiosteally from the lamina on the symptomatic side. Under the operating microscope, limited laminotomy and flavectomy were performed as required. The affected nerve root was mobilized, the disc fragment was removed, and neural decompression was confirmed. The wound was then closed in layers after hemostasis.

Pre-incisional Analgesic Techniques

Pre-LSSI

In the pre-LSSI group, 10 mL of 0.25% bupivacaine was administered without saline dilution before skin incision. After sterile preparation and draping in the prone position, the local anesthetic was first infiltrated into the skin and subcutaneous tissue along the planned incision line. Without completely withdrawing the needle, the needle was then advanced toward the ipsilateral paraspinal muscle layer attached to the spinous process and laminae at the operative level. Multifocal infiltration was performed into the multifidus and adjacent paraspinal muscle tissues on the side of surgery. No additional local anesthetic infiltration was performed after skin incision.

Pre-CEA

In the pre-CEA group, the caudal epidural procedure was performed by the operating surgeon before skin incision, after prone positioning and sterile preparation. A loss-of-resistance technique was not used. Under fluoroscopic guidance, a 20-22-gauge spinal needle was advanced through the sacral hiatus into the caudal epidural space. After needle placement, negative aspiration for blood and cerebrospinal fluid was confirmed. Epidural location was subsequently verified by injection of 1-2 mL of contrast medium, with cephalad epidural spread confirmed on the lateral fluoroscopic view and no fluoroscopic evidence of intravascular or intrathecal distribution. After confirmation of epidural placement, 3 mL of 0.25% bupivacaine (7.5 mg) was diluted with sterile normal saline to a total volume of 10 mL and administered as a single-

shot caudal epidural injection. No failed caudal epidural procedure or repeat needle insertion was recorded. Procedure duration was not systematically documented and therefore could not be reliably retrieved for retrospective analysis.

Control Cohort

Patients in the control cohort underwent standard single-level lumbar microdiscectomy without pre-LSSI or pre-CEA.

These interventions represented two technique-based perioperative analgesia protocols used in clinical practice and were not designed as equal-dose bupivacaine regimens. The pre-LSSI protocol delivered 25 mg of bupivacaine to the surgical site, whereas the pre-CEA protocol delivered 7.5 mg of bupivacaine into the caudal epidural space.

Postoperative Analgesia and Mobilization Protocol

All patients received the same routine postoperative analgesic protocol. Intravenous paracetamol 1 g was administered every 6 hours, with the first dose given during the awakening phase. Additional rescue analgesia was administered according to a pre-defined VAS-based institutional algorithm. Diclofenac 75 mg intravenously was administered for moderate pain (VAS 4-6) and could be repeated if clinically required, with a maximum total dose of 150 mg within 24 hours. For severe pain (VAS ≥7), tramadol 50 mg intravenously was added. No patient-controlled analgesia was used.

Postoperative VAS scores were assessed at rest while patients remained in bed during the early postoperative period. Assessments at the pre-defined time points were performed jointly by the ward nurse and the neurosurgery resident responsible for postoperative care. Rescue analgesia was administered by the same clinical team according to the pre-defined VAS thresholds, which were applied uniformly to all study groups. Because these interventions represented routine clinical care rather than a blinded prospective trial, neither the VAS assessors nor the staff administering rescue analgesia were blinded to the pre-incisional analgesic protocol.

Ambulation time was recorded as the time from surgery to first mobilization. According to the routine postoperative care protocol of the institution, patients were not mobilized before the sixth postoperative hour; therefore, 6 hours represented the earliest permitted ambulation time in this cohort.

Outcomes

VAS-back and VAS-leg scores were recorded preoperatively and at pre-defined postoperative time points: 0, 1, 2, 4, 6, 12, 18, and 24 hours after surgery.

The primary endpoint was cumulative postoperative back pain burden during the first 24 hours, calculated as the AUC of VAS-back scores from 0 to 24 hours using the trapezoidal rule.

Secondary outcomes included VAS-leg AUC from 0 to 24 hours, repeated postoperative VAS-back and VAS-leg trajectories, any rescue analgesic requirement within 24 hours, opioid rescue requirement, time to first rescue analgesia, ambulation time, length of hospital stay, and adverse events. Adverse events

were defined as postoperative nausea/vomiting requiring treatment, urinary retention, clinically apparent new motor block, wound-related complications, neurological deterioration, allergic reaction, or procedure-related complications within the first 24 hours.

Because rescue analgesia could influence subsequent VAS scores, rescue analgesic requirement and time to first rescue analgesia were evaluated as key secondary outcomes and interpreted alongside the VAS AUC and pain trajectory analyses.

Statistical Analysis

Statistical analyses were performed using Jamovi software, version 2.6.26.0 (Sydney, Australia). Continuous variables were summarized as mean $\pm$ standard deviation (SD) or median with interquartile range (IQR) according to distributional characteristics. Categorical variables were summarized as counts and percentages.

The primary analysis compared the two active preemptive analgesia groups: pre-LSSI and pre-CEA. The control cohort was shown descriptively as an exploratory contextual comparator and was not included in the primary hypothesis testing.

The primary endpoint, VAS-back AUC 0-24 h, was calculated using the trapezoidal rule. Between-group comparison of VAS-back AUC was performed using an independent-samples test according to distributional characteristics. VAS AUC values were presented as mean $\pm$ SD for descriptive consistency. AUC values are expressed as VAS score $\times$ hour. Welch's t-test was used for VAS-back AUC. Because VAS-leg AUC showed a skewed distribution with floor effects, the between-group p-value for VAS-leg AUC was calculated using the Mann-Whitney U test. Postoperative VAS trajectories were presented descriptively to illustrate the temporal pattern of pain scores; no repeated-measures one-way analysis of variance or mixed-effects model was performed because the primary longitudinal pain comparison was prespecified as VAS AUC over 24 hours. Categorical outcomes, including rescue analgesic requirement, opioid rescue requirement, and adverse events, were compared using Fisher's exact test or the chi-square test, as appropriate.

Time to first rescue analgesia was summarized among patients who required rescue analgesia. If no rescue analgesic event occurred in one of the active-treatment groups, this outcome was reported descriptively without formal between-group hypothesis testing.

Secondary outcomes were analyzed as exploratory endpoints, and no adjustment for multiple comparisons was applied. For exploratory three-group description, values from the control cohort were presented in tables and figures to provide clinical context. However, p-values in the main tables were restricted to the pre-defined active-treatment comparison between pre-LSSI and pre-CEA. Because 6 hours represented the earliest permitted ambulation time according to institutional routine practice, the proportion of patients ambulating exactly at 6 postoperative hours was also analyzed as an exploratory binary recovery outcome using Fisher's exact test.

A two-sided p-value <0.05 was considered statistically significant for the primary analysis.

No a priori sample size calculation was performed because this was a retrospective analysis of eligible patients treated during the study period.

RESULTS

Study Cohort

During 2022, 458 lumbar microdiscectomy procedures were screened for eligibility. The main reasons for exclusion were multilevel surgery, revision surgery, additional decompressive procedures, fusion procedures, ASA III-IV status, chronic narcotic use, or incomplete perioperative pain records. After application of the inclusion and exclusion criteria, 138 patients were included in the final study cohort. Of these, 47 patients received pre-LSSI, 42 patients received pre-CEA, and 49 patients underwent lumbar microdiscectomy without preemptive analgesia and constituted the exploratory control cohort. The primary active-treatment analysis included 89 patients in the pre-LSSI and pre-CEA groups.

Baseline Characteristics

Baseline demographic and clinical characteristics are summarized in Table 1. The two active-treatment groups were comparable in terms of age, sex, ASA physical status, operated disc level, symptom side, preoperative VAS-back score, and preoperative VAS-leg score. The mean age was 49.6 ± 9.3 years in the pre-LSSI group and 50.1 ± 11.5 years in the pre-CEA group. Preoperative VAS-back scores were low in both active-treatment groups, with a median value of 0 (0-0) in both groups. Preoperative VAS-leg scores were also similar between the pre-LSSI and pre-CEA groups, with median values of 6 (6-8) and 6 (6-7), respectively.

Postoperative Pain Outcomes

Postoperative pain and recovery outcomes are shown in Table 2. The primary endpoint, VAS-back AUC 0-24 h, was significantly lower in the pre-CEA group than in the pre-LSSI group. The mean VAS-back AUC was 64.0 ± 6.0 in the pre-LSSI group and 42.2 ± 8.0 in the pre-CEA group ($p < 0.001$). In the exploratory control cohort, the mean VAS-back AUC was 90.6 ± 11.3 .

VAS-leg AUC 0-24 h was also lower in the pre-CEA group compared with the pre-LSSI group. Because VAS-leg AUC showed a skewed distribution with floor effects, it was summarized as median (IQR). VAS-leg AUC 0-24 h was lower in the pre-CEA group than in the pre-LSSI group [0.0 (0.0-0.0) vs. 8.0 (8.0-8.0); $p < 0.001$]. In the exploratory control cohort, the median VAS-leg AUC was 8.0 (8.0-8.0).

The postoperative VAS trajectories are illustrated descriptively in Figure 1; no repeated-measures statistical model was applied to these trajectory plots. Mean VAS-back scores remained consistently lower in the pre-CEA group than in the pre-LSSI and control cohorts throughout the first 24 postoperative

Table 1. Baseline demographic and clinical characteristics of the study cohort

Variable	Pre-LSSI (n=47)	Pre-CEA (n=42)	Control (n=49)	p-value*
Age, years, mean $\pm$ SD	49.6 $\pm$ 9.3	50.1 $\pm$ 11.5	49.4 $\pm$ 9.9	0.840
Sex, n (%)				1.000
Female	22 (46.8)	20 (47.6)	20 (40.8)	
Male	25 (53.2)	22 (52.4)	29 (59.2)	
ASA status, n (%)				0.674
ASA I	21 (44.7)	21 (50.0)	25 (51.0)	
ASA II	26 (55.3)	21 (50.0)	24 (49.0)	
Operated level, n (%)				0.988
L2-3	3 (6.4)	3 (7.1)	1 (2.0)	
L3-4	7 (14.9)	7 (16.7)	5 (10.2)	
L4-5	16 (34.0)	13 (31.0)	25 (51.0)	
L5-S1	21 (44.7)	19 (45.2)	18 (36.7)	
Symptom side, n (%)				0.832
Left	24 (51.1)	23 (54.8)	25 (51.0)	
Right	23 (48.9)	19 (45.2)	24 (49.0)	
Preoperative VAS-back, median (IQR)	0 (0-0)	0 (0-0)	0 (0-0)	0.881
Preoperative VAS-leg, median (IQR)	6 (6-8)	6 (6-7)	7 (7-7)	0.470

Values are presented as mean $\pm$ SD, median (IQR), or n (%), as appropriate. *: p-values compare the two active-treatment groups (pre-LSSI vs. pre-CEA) only; the control cohort is shown descriptively as an exploratory contextual comparator, ASA: American Society of Anesthesiologists, IQR: Interquartile range, pre-CEA: Pre-incisional caudal epidural analgesia, pre-LSSI: Pre-incisional local surgical-site infiltration, SD: Standard deviation, VAS: Visual analog scale

Table 2. Postoperative pain, analgesic requirement, and recovery outcomes

Outcome	Pre-LSSI (n=47)	Pre-CEA (n=42)	Control (exploratory) (n=49)	p-value*
Pain outcomes				
VAS-back AUC 0-24 h, mean $\pm$ SD	64.0 $\pm$ 6.0	42.2 $\pm$ 8.0	90.6 $\pm$ 11.3	<0.001
VAS-leg AUC 0-24 h, median (Q1-Q3)	8.0 (8.0-8.0)	0.0 (0.0-0.0)	8.0 (8.0-8.0)	<0.001
Rescue analgesia outcomes				
Any rescue analgesic requirement, n (%)	47 (100.0)	0 (0.0)	49 (100.0)	<0.001
Opioid rescue requirement, n (%)	0 (0.0)	0 (0.0)	11 (22.4)	-
Time to first rescue analgesia, h [†]	4 (4-6)	No rescue required	0 (0-0)	-
Recovery and safety outcomes				
Ambulation time, h, median (IQR) [‡]	6 (6-12)	6 (6-6)	18 (12-24)	<0.001
Ambulation at earliest permitted time point (6 h), n (%)	33 (70.2)	42 (100.0)	3 (6.1)	<0.001
Length of hospital stay, days, median (IQR)	1 (1-1)	1 (1-1)	1 (1-1)	-
Adverse events, n (%)	0 (0.0)	0 (0.0)	3 (6.1)	-

Values are presented as mean $\pm$ SD, median (IQR), median (Q1-Q3), or n (%), as appropriate. *: p-values compare the two active-treatment groups (pre-LSSI vs. pre-CEA) only; the control cohort is shown descriptively as an exploratory contextual comparator. Welch's t-test was used for VAS-back AUC. VAS-back AUC values are expressed as VAS score $\times$ hour. Because VAS-leg AUC showed a skewed distribution with floor effects, it is presented as median (Q1-Q3), and the p-value was calculated using the Mann-Whitney U test. The Mann-Whitney U test was used for ambulation time; Fisher's exact test was used for any rescue analgesic requirement and ambulation at the earliest permitted time point. Dashes indicate that no inferential test was performed because both active-treatment groups had zero events, no variance, or no rescue event in the pre-CEA group. [†]: Time to first rescue analgesia was summarized among patients who required rescue analgesia. [‡]: Ambulation time should be interpreted in the context of institutional routine practice, in which patients were not mobilized before 6 postoperative hours. All adverse events in the control cohort were postoperative nausea and vomiting after tramadol administration. AUC: Area under the curve, IQR: Interquartile range, pre-CEA: Pre-incisional caudal epidural analgesia, pre-LSSI: Pre-incisional local surgical-site infiltration, SD: Standard deviation, VAS: Visual analog scale

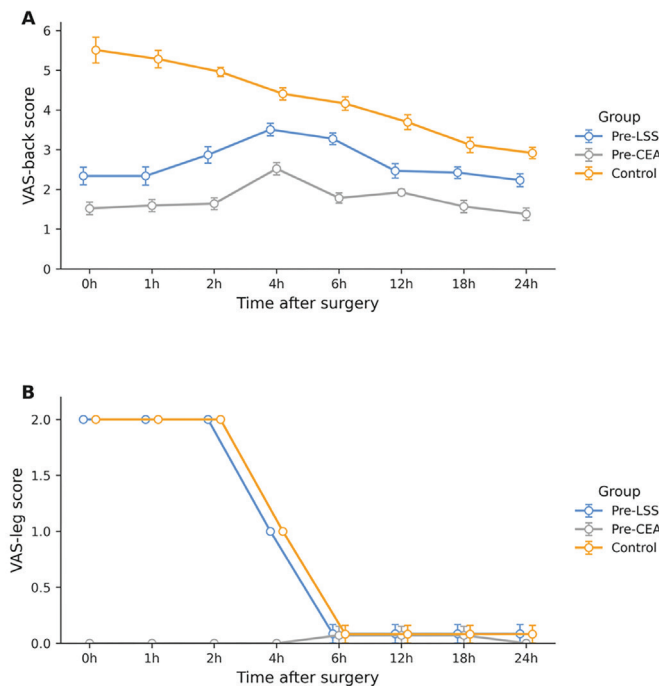


Figure 1. Postoperative VAS-back and VAS-leg trajectories during the first 24 hours after surgery.

Mean postoperative VAS-back (A) and VAS-leg (B) scores are shown for the pre-LSSI, pre-CEA, and exploratory control cohorts across pre-defined postoperative time points. Error bars indicate 95% confidence intervals. Group markers were slightly offset horizontally within each time point to improve visual clarity. Preoperative VAS scores are not displayed and were not included in AUC calculations. The trajectory plots are descriptive and were not analyzed using repeated-measures ANOVA or mixed-effects models, because the primary longitudinal pain comparison was prespecified as VAS AUC over 24 hours. VAS was measured on a 0-10 scale, with higher scores indicating greater pain intensity; the y-axis in panel B was scaled to the observed postoperative range for visual clarity. pre-CEA: Pre-incisional caudal epidural analgesia, pre-LSSI: Pre-incisional local surgical-site infiltration, VAS: Visual analog scale, AUC: Area under the curve, ANOVA: One-way analysis of variance

hours. Mean VAS-leg scores decreased rapidly after surgery in all groups; however, the pre-CEA group showed the lowest early postoperative VAS-leg trajectory.

Rescue Analgesia

Rescue analgesic requirement differed significantly between the two active-treatment groups. All patients in the pre-LSSI group required additional rescue analgesia within the first 24 hours, whereas no patient in the pre-CEA group required rescue analgesia (47/47 vs. 0/42; $p < 0.001$). In the control cohort, all patients required rescue analgesia.

No patient in either active-treatment group required opioid rescue analgesia. In contrast, opioid rescue analgesia was required in 11 patients in the control cohort (22.4%). Among patients who required rescue analgesia, the median time to first rescue analgesia was 4 (4-6) hours in the pre-LSSI group and 0 (0-0) hours in the control cohort. Because no rescue analgesic event occurred in the pre-CEA group, time to first

rescue analgesia was not formally compared between the two active-treatment groups. Although all pre-LSSI patients eventually required rescue analgesia, the median time to first rescue analgesia was longer in the pre-LSSI group than in the exploratory control cohort, suggesting an early analgesic effect relative to no preemptive intervention.

Recovery and Safety Outcomes

Ambulation time distribution differed between the two active-treatment groups. The median ambulation time was 6 (6-12) hours in the pre-LSSI group and 6 (6-6) hours in the pre-CEA group ($p < 0.001$). In the control cohort, the median ambulation time was 18 (12-24) hours. Because the institutional postoperative care protocol did not allow routine mobilization before the sixth postoperative hour, 6 hours represented the earliest permitted ambulation time. When ambulation was analyzed as achievement of the earliest permitted mobilization time, 42 of 42 patients (100.0%) in the pre-CEA group ambulated exactly at 6 hours compared with 33 of 47 patients (70.2%) in the pre-LSSI group ($p < 0.001$). In the exploratory control cohort, 3 of 49 patients (6.1%) ambulated at 6 hours.

Length of hospital stay was similar between the two active-treatment groups, with a median of 1 (1-1) day in both groups. No adverse events were recorded in the pre-LSSI or pre-CEA groups. The three adverse events recorded in the control cohort consisted of postoperative nausea and vomiting occurring after tramadol administration and were therefore considered likely opioid-related events.

DISCUSSION

In this retrospective comparative cohort analysis of prospectively recorded perioperative pain data, pre-CEA was associated with lower early postoperative pain burden than pre-LSSI after single-level lumbar microdiscectomy. Pre-CEA was associated with lower VAS-back and VAS-leg AUCs during the first 24 postoperative hours and no rescue analgesic requirement. The exploratory control cohort showed the highest cumulative VAS-back burden and universal rescue analgesic requirement, providing contextual support for the clinical relevance of preemptive analgesia. Because the study was non-randomized and the primary comparison was pre-defined between the two active pre-incisional techniques, these findings should be interpreted as associations rather than definitive evidence of superiority. In particular, patients who preferred caudal epidural analgesia may have differed from those who preferred local surgical-site infiltration in unmeasured factors such as pain expectations, anxiety, or attitudes toward postoperative analgesia, and these factors may have influenced the observed differences.

Caudal or epidural analgesia and local wound or surgical-site infiltration have been investigated as perioperative analgesic strategies in lumbar disc and decompressive spine surgery. Previous studies have suggested that caudal or epidural

administration of local anesthetics, with or without adjuncts, may reduce early postoperative pain and analgesic consumption after lumbar disc surgery or decompression^(12,14). Similarly, local anesthetic infiltration into the wound, paraspinal muscles, or surgical field has been associated with reduced early pain scores, delayed first analgesic requirement, or lower opioid consumption^(11,15). Broader comparative evidence from regional analgesia studies also supports local and neuraxial techniques as components of multimodal postoperative pain control after lumbar spine surgery⁽⁷⁾. However, these approaches have generally been evaluated against placebo, systemic analgesia, or standard care rather than directly against each other^(7,11,12,14,15). The present study addresses this gap by comparing two practical, technique-based pre-incisional analgesic protocols in the same single-level microdiscectomy setting.

Our findings are consistent with randomized studies suggesting that caudal epidural administration of local anesthetics can improve early postoperative analgesia after lumbar disc and lumbosacral spine surgery. In a randomized prospective study of 120 patients with single-level lumbar disc herniation, Cine and Uysal⁽¹²⁾ evaluated preemptive caudal bupivacaine, with or without methylprednisolone, against caudal saline and reported lower postoperative VAS scores and reduced additional analgesic requirement in the active caudal groups. Kumar et al.⁽¹⁶⁾ also reported in a prospective randomized controlled trial that a single preoperative caudal injection of 0.2% ropivacaine provided effective analgesia in degenerative lumbar spine surgery, further supporting the role of preemptive caudal local anesthetic administration in posterior lumbar procedures. Similarly, Samagh et al.⁽¹³⁾ found lower postoperative VAS scores, reduced intraoperative fentanyl requirement, longer time to rescue analgesia, and no hemodynamic or neurological adverse effects after preemptive caudal ropivacaine. In single-level lumbar discectomy, Hady et al.⁽¹⁷⁾ also reported that adding caudal epidural bupivacaine to general anesthesia reduced intraoperative narcotic consumption, postoperative VAS scores, intravenous analgesic requirement, and postoperative nausea and vomiting. Rajwade et al.⁽¹⁸⁾ showed that caudal ropivacaine with fentanyl prolonged postoperative analgesia compared with ropivacaine alone. Taken together, these studies support the clinical plausibility of our finding that pre-CEA was associated with lower 24-hour VAS-back and VAS-leg pain burden and no rescue analgesic requirement. However, unlike most previous caudal studies, the present study compared pre-CEA directly with a commonly used pre-LSSI protocol.

Local wound or surgical-site infiltration has also been widely studied in lumbar spine surgery, although the magnitude and consistency of its analgesic benefit remain variable. In a systematic review of double-blind randomized trials, Kjærgaard et al.⁽¹⁰⁾ found that local anesthetic wound infiltration reduced pain scores in only a minority of comparisons and produced, at most, small-to-modest reductions in early postoperative pain intensity and opioid consumption. The same review noted that the evidence was difficult to interpret because of heterogeneity

in surgical procedures, infiltration timing, tissue planes, local anesthetic agents, and outcome reporting. More recent reviews focusing on intramuscular or field infiltration have similarly suggested that local infiltration may delay the first analgesic request and modestly reduce early opioid consumption, but its effect on pain scores is often short-lived and most apparent during the immediate postoperative period^(11,15). Importantly, timing may also influence the efficacy of local infiltration. Gurbet et al.⁽¹⁹⁾ reported that pre-emptive levobupivacaine infiltration at the surgical site provided better postoperative analgesia than infiltration administered at closure in lumbar disc surgery. In this context, our pre-LSSI protocol should be interpreted as a practical pre-incisional surgical-site technique targeting the skin, subcutaneous tissue, and ipsilateral multifidus/paraspinal muscle layer rather than as a neuraxial analgesic strategy. The lower VAS-back AUC in the pre-LSSI group compared with the control cohort is consistent with an early somatic analgesic effect of local infiltration; however, the higher cumulative pain burden and universal rescue analgesic requirement compared with pre-CEA suggest less complete early analgesia than caudal epidural delivery.

The current regional analgesia landscape in lumbar spine surgery has expanded substantially with the increasing use of ultrasound-guided fascial-plane blocks. A network meta-analysis of 34 randomized trials involving 2,365 patients compared TLIP, ESPB, wound infiltration, and control strategies and found that TLIP was associated with the greatest reduction in 24-hour opioid consumption, while ESPB and wound infiltration also represented effective regional alternatives⁽⁷⁾. More recent systematic reviews have similarly demonstrated reductions in postoperative pain and opioid consumption with ESPB⁽⁸⁾ and TLIP⁽⁹⁾, although heterogeneity in surgical procedures, block levels, local anesthetic regimens, and comparators remains substantial. These newer techniques avoid intentional neuraxial access and may be particularly attractive within multimodal ERAS pathways. However, the present study did not directly compare pre-CEA with ESPB or TLIP, and our results should not be interpreted as evidence that caudal epidural analgesia is preferable to contemporary fascial-plane blocks. Rather, they suggest that the caudal epidural route remains a potentially relevant technique-based option that warrants direct comparison with contemporary regional strategies in future randomized studies.

The observed difference between pre-LSSI and pre-CEA may be partly explained by the anatomical compartment targeted by each technique. Pre-LSSI primarily addresses somatic nociceptive input from the incision and muscle dissection, consistent with systematic evidence showing that wound infiltration is simple and attractive but heterogeneous, often modest, and mostly limited to the early postoperative period^(10,11). By contrast, caudal epidural injection delivers local anesthetic into the epidural space, where neural blockade may occur at spinal nerve roots and proximal afferent transmission. Samagh et al.⁽¹³⁾ described preemptive caudal epidural analgesia as

blocking sensory input at the spinal cord level, while Rajwade et al.⁽¹⁸⁾ noted that epidural local anesthetic produces neural blockade after fixation to spinal nerve roots. This broader neural target may help explain why pre-CEA was associated with lower VAS-back and VAS-leg AUCs and no rescue analgesic requirement. Importantly, pre-CEA protocol used a lower total bupivacaine dose than pre-LSSI. Therefore, these findings suggest that anatomical targeting may be clinically relevant in early postoperative analgesia after microdiscectomy. However, because dose, dilution, volume, route, and tissue compartment differed simultaneously, this study cannot determine whether the observed association was attributable to anatomical targeting, drug distribution, total dose, or other protocol-related factors. Accordingly, the present study should be regarded as a comparison of two complete, clinically used, non-dose-equivalent analgesic protocols rather than as a controlled comparison of bupivacaine administered through two different anatomical routes. The independent contribution of route cannot be separated from differences in total bupivacaine dose, dilution, distribution, and tissue compartment in the present design. The results should therefore not be interpreted as proof that target compartment is more important than absolute local anesthetic dose.

The clinical relevance of these findings lies primarily in the reduction of early rescue analgesic requirement. Procedure-specific recommendations for lumbar laminectomy emphasize multimodal analgesia and reserve opioids mainly for rescue treatment, reflecting efforts to reduce opioid exposure after spine surgery⁽¹⁾. Similarly, meta-analytic evidence suggests that preemptive analgesia can reduce early postoperative pain and analgesic consumption after lumbar spine surgery, although effects vary according to the technique used⁽²⁾. In the present cohort, no patient in the pre-CEA group required rescue analgesia during the first 24 postoperative hours, whereas all patients in the pre-LSSI and control cohorts required additional analgesia. This finding suggests that the pre-CEA protocol was associated not only with lower pain intensity but also with less need for supplemental postoperative medication. However, because opioid rescue was not required in either active-treatment group, our results should not be interpreted as demonstrating an opioid-sparing advantage of pre-CEA over pre-LSSI. Rather, the main clinical distinction between the two active techniques was the absence of rescue analgesic requirement in the pre-CEA group. Ambulation findings should also be interpreted cautiously: although the pre-CEA patients reached the earliest permitted mobilization time more consistently, institutional protocol did not allow routine ambulation before the sixth postoperative hour. Therefore, this result should be considered a marker of smoother early recovery rather than proof of accelerated mobilization. Length of hospital stay was similar between active-treatment groups, suggesting that the benefit of pre-CEA was most evident in early pain control rather than discharge timing.

The complete absence of rescue analgesic requirement in the pre-CEA group deserves particular caution because the magnitude of this association appears stronger than that generally reported in previous randomized studies of caudal epidural analgesia. Earlier studies have predominantly demonstrated lower postoperative pain scores, reduced analgesic consumption, or a longer time to first rescue medication rather than universal avoidance of rescue analgesia during the first 24 hours^(12,13,16-18). In our protocol, all patients received scheduled intravenous paracetamol, and rescue treatment was triggered by a standardized resting VAS threshold of ≥ 4 . Thus, the absence of rescue medication in the pre-CEA cohort was consistent with the pre-defined institutional algorithm. Nevertheless, this striking finding should not be interpreted as proof of an unusually strong causal effect of caudal epidural analgesia. Patient-preference-based treatment selection, unmeasured differences in pain expectations or anxiety, the absence of assessor blinding, the relatively modest sample size, and differences in bupivacaine dose and drug distribution between the protocols may all have contributed to the observed effect size. Confirmation in a randomized, blinded, dose-standardized comparison is therefore particularly important.

From a practical standpoint, pre-CEA appears feasible because it can be performed after prone positioning without changing the operative setup. However, caudal epidural analgesia remains a neuraxial intervention and carries potential procedure-related risks. Reported complications of epidural and neuraxial techniques include inadvertent intravascular, intrathecal, or subdural injection, epidural hematoma, infection or epidural abscess, direct neural injury, local anesthetic systemic toxicity, motor blockade, urinary retention, and hemodynamic effects such as hypotension^(20,21). Although serious neurological complications are uncommon, their potential severity requires careful patient selection, strict aseptic technique, accurate needle positioning, and appropriate monitoring^(20,21). Previous randomized studies of caudal analgesia in lumbar surgery have also reported acceptable short-term safety profiles, with no major hemodynamic, neurological, or block-related complications in the studies by Samagh et al.⁽¹³⁾, Hady et al.⁽¹⁷⁾, and Rajwade et al.⁽¹⁸⁾. In our protocol, negative aspiration for blood or cerebrospinal fluid was followed by fluoroscopic contrast confirmation of epidural spread before local anesthetic administration; no failed procedure, repeat needle insertion, clinically apparent motor block, urinary retention, or other procedure-related adverse event was documented in the pre-CEA cohort. No adverse events were observed in either active-treatment group, whereas the three adverse events recorded in the control cohort consisted of postoperative nausea and vomiting after tramadol administration. These events should therefore be interpreted as likely opioid-related events rather than as evidence of a direct comparative safety advantage of either pre-incisional technique. Nevertheless, the absence of procedure-related complications among

42 pre-CEA patients cannot establish procedural safety or reliably estimate the incidence of uncommon adverse events. Contemporary fascial-plane techniques such as ESPB and TLIP avoid intentional epidural access and may therefore offer a different procedural risk profile when selecting among regional analgesic strategies.

Study Limitations

This study has several limitations. First, although perioperative pain data were recorded prospectively using pre-defined time points, the present analysis was retrospective and non-randomized. In particular, treatment selection may have been influenced by patient preference, surgeon-patient discussion, pain expectations, anxiety, or perceived need for neuraxial analgesia; therefore, residual confounding and selection bias cannot be excluded. Second, neither patients nor outcome assessors were blinded, which may have affected subjective VAS reporting and rescue analgesic administration. Although rescue analgesia was administered according to a pre-defined VAS-based algorithm, the absence of blinding may have influenced subjective VAS reporting or clinical administration of rescue medication. Third, the pre-LSSI and pre-CEA protocols were not dose-equivalent bupivacaine regimens; thus, the study should be interpreted as a comparison of clinical technique-based protocols rather than a pharmacologic dose-response comparison. Although the intraoperative opioid protocol was standardized and no additional opioid or remifentanyl was used after the fentanyl induction dose, individual volatile anesthetic concentrations and MAC values were not reliably retrievable from the retrospective records. Consequently, residual confounding related to anesthetic depth or volatile anesthetic exposure cannot be completely excluded. Fourth, rescue analgesia may have influenced subsequent VAS scores, although this was addressed by evaluating VAS AUC and rescue analgesic requirement together. Fifth, this single-center study included only single-level lumbar microdiscectomy patients with 24-hour follow-up, limiting generalizability to multilevel surgery, fusion, revision procedures, and longer-term outcomes. Finally, the control cohort was retained only as an exploratory contextual comparator and was not part of the primary active-treatment hypothesis. In addition, because no a priori sample size calculation was performed, the study may have been underpowered for secondary outcomes with low event rates, including opioid rescue requirement and adverse events. Future prospective randomized studies with blinded outcome assessment, standardized local anesthetic dosing, pre-defined opioid-equivalent consumption metrics, patient satisfaction measures, discharge-readiness criteria, and longer follow-up are needed to determine whether pre-CEA is associated with reproducible clinical benefits over local surgical-site infiltration after lumbar microdiscectomy.

CONCLUSION

In patients undergoing single-level lumbar microdiscectomy, pre-CEA was associated with lower early postoperative VAS-back and VAS-leg pain burden than pre-LSSI. Pre-CEA was also associated with no rescue analgesic requirement during the first 24 postoperative hours, whereas rescue analgesia was required in all patients receiving pre-LSSI. The exploratory control cohort further supported the clinical relevance of preemptive analgesia by showing the highest postoperative back pain burden and universal rescue analgesic use. These findings suggest that the anatomical target of pre-incisional analgesia may be important for early postoperative pain control after lumbar microdiscectomy. However, because this was a non-randomized, non-dose-standardized analysis, prospective randomized dose-standardized studies are required to determine whether pre-CEA is associated with reproducible clinical benefits over local surgical-site infiltration.

Ethics

Ethics Committee Approval: The study was approved by the University of Health Sciences Türkiye, Prof. Dr. Cemil Taşcıoğlu City Hospital Ethics Committee before data analysis (approval no: 22, date: 23.01.2023) and was conducted in accordance with the principles of the Declaration of Helsinki.

Informed Consent: Written informed consent for surgery and perioperative analgesic procedures was obtained according to institutional practice.

Footnotes

AI-based language editing assistance was used in this manuscript preparation. The authors reviewed, verified, and take full responsibility for the scientific content, data accuracy, interpretation, and final version of the manuscript.

Authorship Contributions

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

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study received no financial support.

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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^(1,2).

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^(2,3).

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Received: 28.07.2026 **Accepted:** 25.08.2026 **Publication Date:** 14.10.2026

Cite this article as: Orunoğlu M, Meral M, Yaşar S. Early motion preservation but converging two-year outcomes after cervical disc arthroplasty versus anterior cervical discectomy and fusion: a retrospective cohort study. J Turk Spinal Surg. 2026;37(4):165-175



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⁽⁴⁾.

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⁽⁴⁾. 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⁽⁵⁾. 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^(6,7).

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 ≤ -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^(2,3).

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⁽⁴⁾.

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^(1,5).

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^(8,9). 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⁽⁸⁾. 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⁽¹⁰⁾.

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^(11,12). 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 6th month, 1st year, and 2nd year follow-ups. The postoperative 6th month was considered the early follow-up period, the 1st year was considered the mid-term follow-up period, and the 2nd year was considered the late follow-up period^(6,7).

Pain Score

Pain intensity was evaluated using the VAS, a widely used unidimensional measure of self-reported pain intensity^(13,14). 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^(4,6,7).

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 ± 9.6 years in the ACDF/cage group and 44.5 ± 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) mean $\pm$ SD	CDA/prosthesis group (n=46) 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 ²	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^(15,16).

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⁽¹⁷⁾.

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) mean ± SD	CDA/prosthesis group (n=46) 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) mean ± SD	CDA/prosthesis group (n=46) 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^(18,19).

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^(19,20).

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) n (%)	CDA/prosthesis group (n=46) 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
Heterotopic ossification in CDA group, n (%)			
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^(16,19).

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^(21,22). 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^(8,9).

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⁽²³⁾.

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⁽²⁴⁾.

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.

Acknowledgements

The authors would like to thank all healthcare professionals who contributed to the clinical management, follow-up, and data collection of the patients included in this study.

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.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study received no financial support.

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SPINAL ANESTHESIA FOR UNILATERAL BIPORTAL ENDOSCOPIC LUMBAR DECOMPRESSION IN PATIENTS WITH SIGNIFICANT COMORBIDITIES: FEASIBILITY AND EARLY OUTCOMES

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ABSTRACT

Objective: The objective of this study is to evaluate the feasibility, perioperative safety, and early clinical outcomes of unilateral biportal endoscopic lumbar decompression (UBELD) performed under spinal anesthesia in carefully selected patients.

Materials and Methods: A retrospective review was conducted on patients who underwent UBELD under spinal anesthesia between April 2024 and June 2025. Cases from two different centers were included in the study. The primary outcome was the successful completion of surgery under spinal anesthesia without conversion to general anesthesia. Secondary outcomes included anesthesia-related adverse events, operative time, surgical complications, and changes in visual analog scale (VAS) scores for back and leg pain and in Oswestry disability index (ODI) scores.

Results: The mean operative time was 71.5±18.9 minutes. Mild intravenous sedation was required in 10 patients (45.5%). Transient hypotension was observed in five patients (22.7%), bradycardia in two patients (9.1%), and postoperative nausea in four patients (18.2%). Complications included an incidental dural tear, a postoperative spinal epidural hematoma requiring surgical evacuation, and transient urinary retention, each in one patient. Back pain VAS decreased from 7.27±1.76 preoperatively to 2.64±0.85, corresponding to a mean improvement of 4.64 points [95% confidence interval (CI), 3.89-5.38; p<0.001]. Leg pain VAS decreased from 8.50±1.50 to 2.18±0.85, with a mean improvement of 6.32 points (95% CI, 5.66-6.98; p<0.001). ODI decreased from 65.41±14.78 to 13.64±7.29, corresponding to a mean improvement of 51.77 points (95% CI, 44.38-59.16; p<0.001).

Conclusion: In our study, we observed that UBELD could be performed under spinal anesthesia in a small, carefully selected group of American Society of Anesthesiologists III-IV patients, and we completed all procedures without switching to general anesthesia. Our findings should not be interpreted as evidence that spinal anesthesia is safer than general anesthesia, but rather as evidence of the feasibility of spinal anesthesia in selected patients.

Keywords: Biportal endoscopic surgery, spinal anesthesia, minimally invasive, spinal endoscopy, awake surgery

INTRODUCTION

Degenerative spinal disorders are among the leading causes of pain, disability, and reduced quality of life in the elderly population^(1,2). In degenerative conditions such as lumbar stenosis and lumbar disc herniation, the first-line treatment is conservative^(3,4). Surgical decompression is indicated for patients whose symptoms persist despite medical treatment and physical therapy, or who have progressive neurological deficits⁽⁴⁻⁶⁾. As in all subspecialties of surgery, minimally invasive approaches have now become a routine part of spinal surgery⁽⁷⁾. Among the popular minimally invasive approaches, unilateral biportal endoscopic (UBE) surgery accelerates the postoperative

recovery process by reducing damage to the paraspinal muscles and bone⁽⁸⁾. Thanks to early mobilization, minimal postoperative pain, and the wide range of maneuverability it provides to the surgeon, the frequency of routine use of minimally invasive approaches is increasing^(9,10).

Worldwide, UBE lumbar decompression (UBELD) procedures are generally performed routinely under general anesthesia^(8,11,12). Some patients with degenerative spinal conditions are elderly and have comorbidities, which put them at high risk for anesthesia-related complications. For this group of patients with cardiac, pulmonary, and neurological problems, spinal anesthesia is an important alternative for avoiding complications associated with general anesthesia^(13,14).

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Received: 06.08.2026 **Accepted:** 23.09.2026 **Publication Date:** 14.10.2026

Cite this article as: Karırmzada G, Evleksiz D, Doğan A, Ezgü MC, Özer Mİ, Solmaz İ. Spinal anesthesia for unilateral biportal endoscopic lumbar decompression in patients with significant comorbidities: feasibility and early outcomes. J Turk Spinal Surg. 2026;37(4):176-184



Spinal/epidural anesthesia is gaining increasing attention in lumbar spine surgery for patients with serious comorbidities^(14,15). It has been used for years in cases operated on using a microsurgical approach, and extensive case series evaluating its safety and outcomes have been reported⁽¹³⁾. However, evidence regarding the use of spinal anesthesia during UBELD is limited, particularly in the elderly and high-risk patient groups. There are very few studies in the literature that specifically evaluate the feasibility and perioperative safety of spinal anesthesia for UBELD in high-risk patients⁽¹⁶⁾.

Although the number of studies is limited, previous studies have reported that UBELD can be performed under spinal or local anesthesia in conscious, elderly patients with high-risk medical conditions. In this study, we aimed to report on the feasibility of intrathecal spinal anesthesia, early clinical outcomes, and perioperative events in carefully selected American Society of Anesthesiologists (ASA) III-IV patients.

MATERIALS AND METHODS

This retrospective multicenter study was conducted after obtaining approval for the multicenter study from the Hitit University Faculty of Medicine Institutional Ethics Committee (approval no: 2025-124, date: 03.06.2025). The study was conducted in accordance with the principles of the Declaration of Helsinki. Patients who underwent UBELD surgery under spinal anesthesia at two different centers approved by the ethics committee between April 2024 and June 2025 were analyzed retrospectively. The study included adult patients classified as ASA III or IV who underwent UBELD under spinal anesthesia and had at least three months of postoperative follow-up and patients aged 18 years and older. Patients who underwent UBELD due to spinal infection, tumor, or traumatic pathology, as well as those with incomplete medical records or inadequate follow-up, were excluded from the study. A total of 22 patients met the inclusion criteria and were included in the final analysis. The cases included in the study do not encompass all UBELD procedures performed under spinal anesthesia. The study includes selected cases that met the inclusion criteria. All patients first underwent routine preoperative cardiac, neurological, and pulmonary evaluations and were approved for general anesthesia with an ASA III or IV score. In UBELD cases, the decision to administer spinal anesthesia was made by the anesthesia team in the operating room. When making this decision, the team evaluated the appropriateness of the procedure in consultation with the surgical team, taking into account factors such as the anticipated duration of surgery, the complexity of the procedure, the number of levels to be operated on, and the level of cooperation expected from the patient.

The primary endpoint was procedural feasibility, defined as completion of UBELD under spinal anesthesia without conversion to general anesthesia. Secondary endpoints included operative time, anesthesia-related adverse events (hypotension,

bradycardia, vasopressor use, postoperative nausea, additional local anesthetic requirements, and conversion to general anesthesia), length of hospital stay, and surgical complications. The overall available postoperative follow-up duration was recorded separately and was not used as the time point for the standardized clinical outcome analysis. Clinical relevance was additionally evaluated using previously established minimum clinically important difference (MCID) thresholds for lumbar spine surgery: an improvement of ≥ 1.2 points for back pain visual analog scale (VAS), ≥ 1.6 points for leg pain VAS, and ≥ 12.8 points for Oswestry disability index (ODI)⁽¹⁷⁾.

Anesthesia Technique

Spinal anesthesia was administered while the patient was in a sitting position. Following skin preparation and sterile draping, a 25-gauge Quincke spinal needle was inserted into the L3-L4 or L4-L5 intervertebral space using a midline approach. After confirming the free flow of clear cerebrospinal fluid, 12.5 mg (2.5 mL) of 0.5% hyperbaric bupivacaine was injected intrathecally. The patients were then placed in the supine position, and the sensory block was assessed using a needle-prick test. Before the patients were placed in the prone position and surgery was initiated, a sensory block level extending to T10 or higher was confirmed. Hemodynamic parameters were recorded at regular intervals, and when hypotension or bradycardia occurred, they were treated according to routine anesthetic practices. The duration of the sensory block and the time to block resolution were not recorded.

In cases where the patient's prolonged immobility in the prone position causes position-related discomfort and psychological distress, sedoanalgesia was administered to ensure that this situation did not adversely affect surgical conditions. For this purpose, a combination of midazolam and fentanyl was chosen. Sedation was individually titrated to preserve spontaneous ventilation and airway reflexes. Electrocardiography, non-invasive blood pressure, and peripheral oxygen saturation were monitored throughout the procedure.

Antithrombotic Therapy Management

In the management of patients on antithrombotic therapy, aspirin was not discontinued prior to surgery; clopidogrel was discontinued 5 days before surgery; and apixaban was discontinued 72 hours before surgery. Once clopidogrel and apixaban were discontinued, enoxaparin bridge therapy was initiated, and the final preoperative dose of enoxaparin was administered 12 hours before spinal anesthesia. 24 hours after surgery, patients resumed their regular antithrombotic therapy.

Surgical Technique

All surgeries were performed under spinal anesthesia using a UBE technique (Figures 1-3). Skin incisions and triangulation were standardized by modifying a previously defined method to accommodate the patient's anatomical characteristics and the surgeon's ergonomic needs⁽¹⁸⁾. Irrigation was provided by gravity from a saline bag positioned at a height of 1.7 meters.

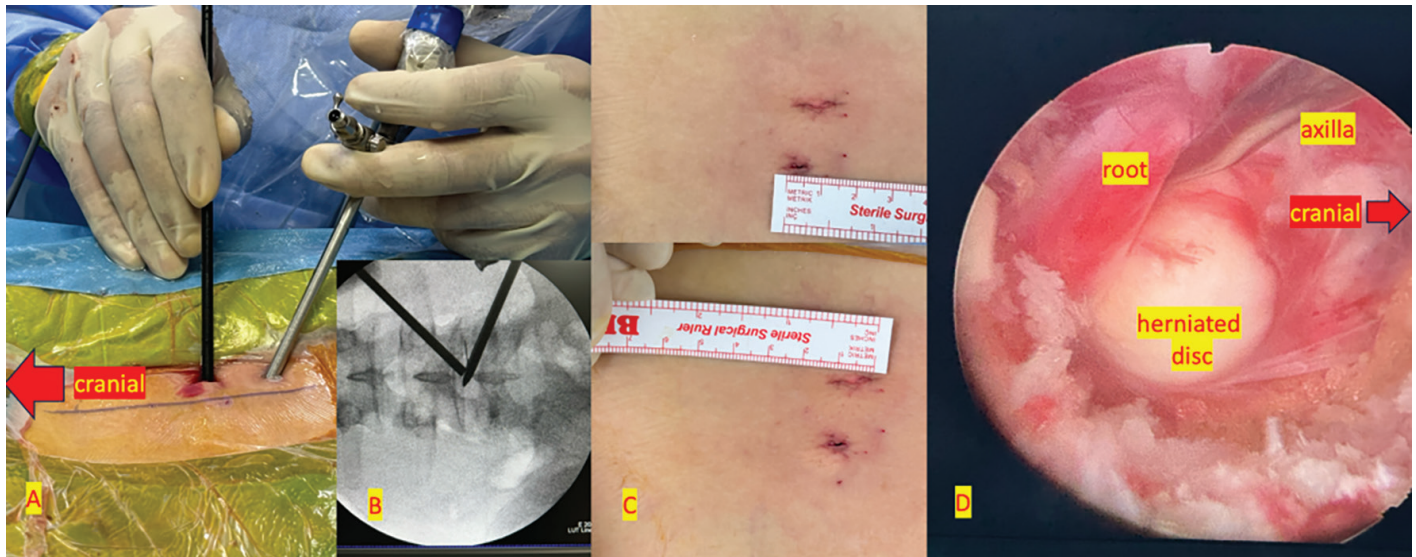


Figure 1. Surgical setup and portal configuration for unilateral biportal endoscopic lumbar decompression under spinal anesthesia. (A) Unilateral biportal endoscopic approach to a right L4-5 lumbar disc herniation. Two portals were established, the endoscope was handled with the surgeon's left hand. The cranial direction is indicated by the red arrow. (B) Intraoperative fluoroscopic view illustrating the triangulation of the viewing and working portals toward the target surgical level. (C) Postoperative small skin incisions used for the viewing and working portals. (D) Endoscopic view showing the decompressed nerve root and the herniated disc fragment before discectomy

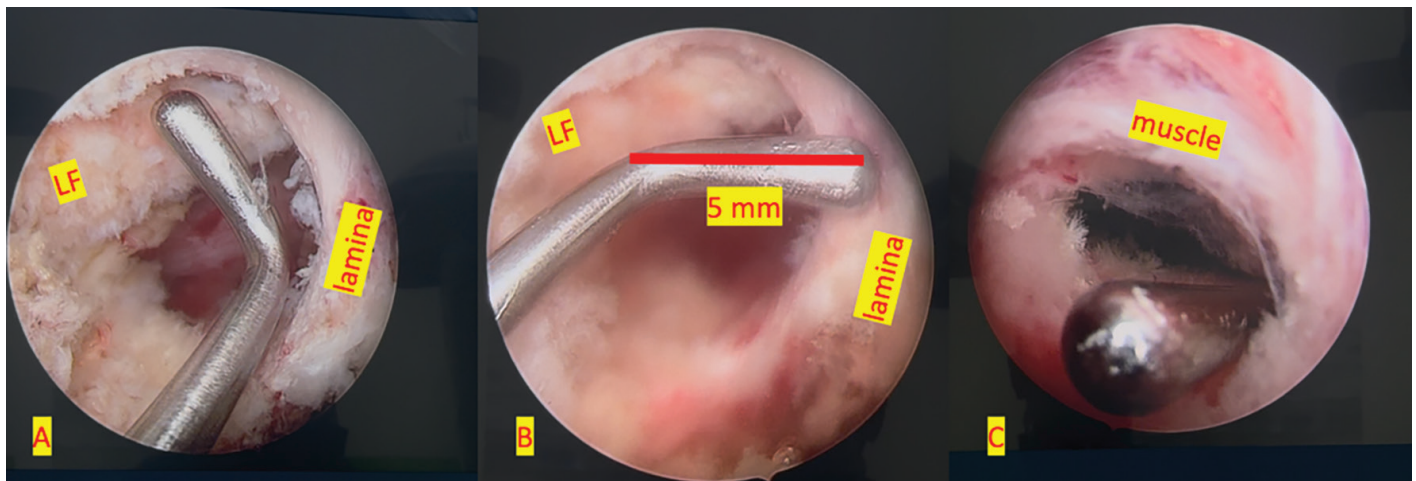


Figure 2. Right-sided L4-L5 key-hole unilateral biportal endoscopic lumbar discectomy performed using a 30° endoscope. (A, B) Endoscopic views demonstrating the key-hole laminotomy. A 5x5 mm bony window (5 mm verticalx5 mm horizontal) was created using a high-speed drill. The ligamentum flavum (LF) was preserved during drilling, and the subsequent flavectomy window was smaller than the laminotomy window. Following flavectomy, discectomy was performed through this limited exposure while preserving the surrounding osseous structures. (C) Endoscopic view at the completion of surgery after cessation of irrigation. The paraspinal muscles returned spontaneously to their anatomical position, and the working portal collapsed spontaneously, demonstrating the muscle-sparing and bone-preserving nature of UBELD. UBELD: Unilateral biportal endoscopic lumbar decompression

A manual pump was used intermittently as needed to improve visual clarity. Irrigation pressure was not measured directly. Potential clinical manifestations associated with increased irrigation pressure were monitored indirectly by observing headaches, an increase in systolic blood pressure, hemorrhages in the epidural space, and pulsations in the dural sac. In cases where two-level decompression was performed, a three-portal configuration was used. In left-sided approaches, to ensure unidirectional (viewing portal -> working portal)

irrigation flow, the caudal level was decompressed first. When proceeding to the cranial level, the initial viewing portal was dilated and reused as the working portal, and an additional portal was created to reestablish the viewing-working portal configuration. In right-sided approaches, the sequence was reversed: the cranial level was treated first, followed by the caudal level. In cases where bilateral decompression was performed, decompression on the contralateral side was performed using a unilateral sublaminar approach.

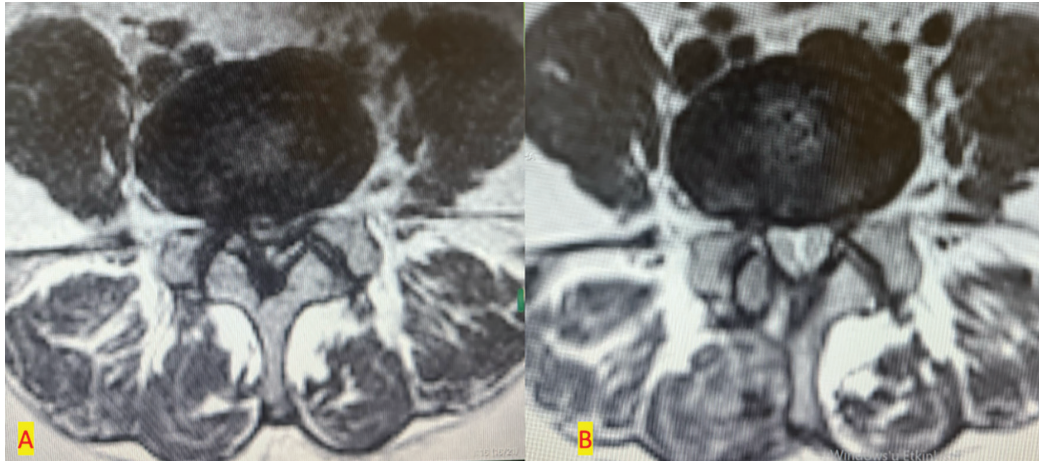


Figure 3. Right-sided UBELD for L4-L5 lumbar spinal stenosis using a 30° endoscope. (A) Preoperative axial T2-weighted MRI demonstrating severe central canal stenosis with compression of the thecal sac and bilateral lateral recess stenosis. (B) Six-month postoperative axial T2-weighted MRI demonstrating adequate decompression of the central canal and bilateral lateral recesses following a right-sided approach. The patient's preoperative symptoms resolved completely, and no evidence of fatty degeneration was observed in the paraspinal muscles on the operated (right) side, indicating preservation of the paraspinal musculature. UBELD: Unilateral biportal endoscopic lumbar decompression, MRI: Magnetic resonance imaging

Statistical Analysis

IBM SPSS Statistics software version 28.0.1.0 (IBM, SPSS, Chicago, Illinois, USA) was used for the statistical analysis of this study data. Numerical variables of patient data were expressed as mean $\pm$ standard deviation, whereas categorical variables are summarized as frequencies and percentages. The distribution of continuous variables was assessed using the Shapiro-Wilk test. Changes in normally distributed paired variables were analyzed using the paired-samples t-test, while non-normally distributed paired variables were compared using the Wilcoxon signed-rank test. All statistical tests were two-tailed, and a p-value <0.05 was considered statistically significant. For each clinical outcome, the magnitude of improvement was calculated as the preoperative score minus the 3-month postoperative score and is reported with its 95% confidence interval (CI). The proportion of patients achieving the predefined MCID threshold was calculated for each outcome and reported as number and percentage.

RESULTS

The mean age of the patients included in the study was 66.7 ± 8.8 years (range, 55-80 years). Seven patients (31.8%) were male and 15 (68.2%) were female. Eighteen patients (81.8%) were classified as ASA III, and four patients (18.2%) were classified as ASA IV. A high burden of systemic comorbidities was observed in the study population. Thirteen patients (59.1%) had hypertension, 14 patients (63.6%) had coronary artery disease, 10 patients (45.5%) had diabetes mellitus, 7 patients (31.8%) had cardiac arrhythmia, 4 patients (18.2%) had a rheumatological disease, 5 patients (22.7%) had a history of previous stroke, 2 patients (9.1%) had Parkinson's disease, and 2 patients (9.1%) had myasthenia gravis. Most patients were receiving

antithrombotic therapy prior to surgery. The mean overall available postoperative follow-up was 7.3 ± 2.7 months, whereas clinical outcome measures were evaluated at the predefined 3-month assessment point. Detailed baseline characteristics are summarized in Table 1. The mean operative time in the study was 71.5 ± 18.9 minutes. Mild intravenous sedation was required in 10 patients (45.5%) during spinal anesthesia, and additional paraspinal local anesthetic infiltration was required in 2 patients (9.1%). Transient hypotension was observed in 5 patients (22.7%), while bradycardia developed in 2 patients (9.1%). Atropine and ephedrine were administered to 2 (9.1%) and 5 (22.7%) patients, respectively. Postoperative nausea was observed in 4 patients (18.2%). Perioperative findings are summarized in Table 2. Clinical outcomes improved at the 3-month assessment. Back pain VAS decreased from 7.27 ± 1.76 preoperatively to 2.64 ± 0.85 , corresponding to a mean improvement of 4.64 points (95% CI, 3.89-5.38; $p < 0.001$). Leg pain VAS decreased from 8.50 ± 1.50 to 2.18 ± 0.85 , with a mean improvement of 6.32 points (95% CI, 5.66-6.98; $p < 0.001$). ODI decreased from 65.41 ± 14.78 to 13.64 ± 7.29 , corresponding to a mean improvement of 51.77 points (95% CI, 44.38-59.16; $p < 0.001$). The MCID threshold was reached by all 22 patients (100%) for both back and leg pain VAS and by 21 patients (95.5%) for ODI (Table 3).

All patients successfully underwent UBELD under spinal anesthesia. Of the patients included in the study, 10 (45.5%) underwent surgery for lumbar disc herniation, while 12 (54.5%) underwent surgery for lumbar stenosis. Among the patients who underwent surgery for disc herniation, eight received single-level UBELD, and two received two-level UBELD. Nine patients operated on for stenosis underwent single-level UBELD, while three patients underwent two-level UBELD. A total of 27 levels were treated. The most commonly treated level was L4-5 ($n=15$,

Table 1. Baseline demographic and clinical characteristics of patients undergoing unilateral biportal endoscopic lumbar decompression under spinal anesthesia

Variable	Overall (n=22)
Age (years), mean $\pm$ SD	66.7 $\pm$ 8.8
Sex, n (%)	
Female	15 (68.2%)
Male	7 (31.8%)
ASA, n (%)	
ASA III	18 (81.8%)
ASA IV	4 (18.2%)
Hypertension, n (%)	13 (59.1%)
Diabetes mellitus, n (%)	10 (45.5%)
Coronary artery disease, n (%)	14 (63.6%)
Cardiac arrhythmia, n (%)	7 (31.8%)
Previous stroke, n (%)	5 (22.7%)
Myasthenia gravis, n (%)	2 (9.1%)
Rheumatologic disease, n (%)	4 (18.2%)
Parkinson disease, n (%)	2 (9.1%)
Antithrombotic therapy, n (%)	
None	4 (18.2%)
Aspirin	9 (40.9%)
Clopidogrel (plavix)	7 (31.8%)
Apixaban (eliquis)	2 (9.1%)
Overall available postoperative follow-up (months), mean $\pm$ SD	7.3 $\pm$ 2.7

Data are presented as mean $\pm$ standard deviation (SD) for continuous variables and number (%) for categorical variables. ASA: American Society of Anesthesiologists

Table 2. Operative and perioperative characteristics

Variable	Overall (n=22)
Operative characteristics	
Operative time (min), mean $\pm$ SD	71.5 $\pm$ 18.9
Hospital stay (hours), mean $\pm$ SD	22.9 $\pm$ 6.0
Approach, n (%)	
Left-sided	17 (77.3%)
Right-sided	5 (22.7%)
Pathology	
Disc herniation	10 (45.5%)
Spinal stenosis	12 (54.5%)
Single level 17	
Two levels 5	
Total levels: 27	
Anesthesia-related events	
Mild intravenous sedation required, n (%)	10 (45.5%)
Additional local anesthetic infiltration, n (%)	2 (9.1%)
Hypotension, n (%)	5 (22.7%)
Bradycardia, n (%)	2 (9.1%)
Atropine administration, n (%)	2 (9.1%)
Ephedrine administration, n (%)	5 (22.7%)
Postoperative nausea, n (%)	4 (18.2%)

Data are presented as mean $\pm$ standard deviation (SD) for continuous variables and number (%) for categorical variables

Table 3. Clinical outcomes following unilateral biportal endoscopic lumbar decompression

Variable	Preoperative	3-month follow-up	Mean improvement (95% CI)	MCID achieved, n (%)	p-value
Back pain VAS	7.27±1.76	2.64±0.85	4.64 (3.89-5.38)	22 (100%)	<0.001*
Leg pain VAS	8.50±1.50	2.18±0.85	6.32 (5.66-6.98)	22 (100%)	<0.001*
ODI	65.41±14.78	13.64±7.29	51.77 (44.38-59.16)	21 (95.5%)	<0.001*

Data are presented as mean ± standard deviation. Improvement was calculated as the preoperative score minus the 3-month postoperative score. MCID was defined as an improvement of ≥1.2 points for back pain VAS, ≥1.6 points for leg pain VAS, and ≥12.8 points for ODI, based on previously established thresholds for lumbar spine surgery. *: Wilcoxon signed-rank test, ^: Paired samples t-test, VAS: Visual analog scale, ODI: Oswestry disability index, CI: Confidence interval, MCID: Minimum clinically important difference

55.6%), followed by L5-S1 (n=6, 22.2%), L3-4 (n=3, 11.1%), L2-3 (n=2, 7.4%), and L1-2 (n=1, 3.7%). The operative descriptive data for the cases included in the study are presented in Table 4. Complications were observed in three patients (13.6%). One patient (4.5%) developed a dural tear, which was repaired with a sponge graft. One patient (4.5%) developed a postoperative epidural hematoma; the patient, who had severe radicular pain, underwent a second UBE procedure to evacuate the hematoma. One patient (4.5%) developed urinary retention 12 hours postoperatively. Since the patient also had concomitant prostatic hypertrophy, he was referred to urology and monitored with a urinary catheter. He returned to normal 10 days later (Table 5). In the third postoperative month, one patient (4.5%) underwent a transforaminal steroid injection due to epidural fibrosis. Subsequently, endoscopic adhesiolysis was performed because pain relief was insufficient.

DISCUSSION

Our study evaluates the feasibility of performing UBE lumbar surgery under spinal anesthesia in patients with high perioperative anesthesia risk due to comorbid conditions and in elderly patients. Our results demonstrate the feasibility of spinal anesthesia for UBELD in ASA III-IV patients with serious comorbidities. In all cases included in the study, UBELD was completed without switching to general anesthesia. The early follow-up results for the patients are encouraging. The successful management of anesthesia-related side effects, combined with the procedure's sustainability and reproducibility, demonstrates that spinal anesthesia is a suitable option for UBELD in selected patients. Along with advances in healthcare and the resulting increase in

life expectancy, the global rise in the elderly patient population has also affected the average age of patients undergoing spinal surgery, and the increasing prevalence of comorbidities in these cases is making procedures increasingly complex⁽¹⁹⁾. In these cases, cardiovascular diseases, diabetes mellitus, neurovascular diseases, chronic rheumatological diseases, and pulmonary disorders have significantly increased the risks associated with perioperative general anesthesia⁽²⁰⁾. General anesthesia is the standard protocol in spinal surgery, and the majority of procedures are performed under general anesthesia. However, in high-risk patient groups, it can lead to adverse outcomes such as hemodynamic fluctuations, pulmonary complications, and the need for intensive care. For example, in one study, the major and minor complications of minimally invasive surgery were analyzed in 21 patients over the age of 80, and it was found that there was a mortality rate of 9.5% due to pulmonary embolism and sepsis⁽⁷⁾. In the study in question, postoperative confusion was observed in 5 patients (24%), liver failure in 1 patient (5%), and transient hypoxia in 2 patients (10%). In a meta-analysis evaluating 7.820 cases and including 38 studies, awake spinal anesthesia was compared with general anesthesia in spinal surgery. It was found that the rates of overall complications, postoperative retention, nausea, and vomiting were statistically significantly higher in the group that received general anesthesia⁽²¹⁾. In another study involving 438 high-risk patients, when patients who underwent surgery under spinal anesthesia were compared with those under general anesthesia, the general anesthesia group was found to have a longer recovery time, greater postoperative analgesic requirements, a longer time spent in the operating room, and a higher overall complication rate⁽²⁰⁾.

Table 4. The operative descriptive data of patients

Subgroup	n	Operative time, min	IV sedation, n (%)	Additional local anesthesia, n (%)	Hypotension, n (%)	Bradycardia, n (%)	Nausea, n (%)
Disc herniation	10	62.5±12.5	4 (40)	1 (10.0)	3 (30)	1 (10)	3 (30)
Spinal stenosis	12	79±20.4	6 (50)	1 (8.3)	2 (16.6)	1 (8.3)	1 (8.3)
Single-level	17	64±11.1	8 (47.1)	2 (11.8)	2 (11.8)	2 (11.8)	3 (17.6)
Two-level	5	97±17.9	2 (40)	0	3 (60)	0	1 (20)
Unilateral decompression	8	62±13.2	3 (37.5)	0	3 (37.5)	1 (12.5)	3 (37.5)
Bilateral decompression	14	76.9±19.8	7 (50)	2 (14.3)	2 (14.3)	1 (7.1)	1 (7.1)

IV: Intravenous

Table 5. Perioperative complications and reinterventions

Variable	Overall (n=22)
Overall perioperative or postoperative adverse events, n (%)	
No complication	19 (86.4%)
Dural tear	1 (4.5%)
Epidural hematoma	1 (4.5%)
Transient urinary retention	1 (4.5%)
Reinterventions, n (%)	
No reintervention	20 (90.9%)
Pain management intervention (algology)	1* (4.5%)
Endoscopic revision surgery	2 (9.1%)
*: One patient underwent both pain management intervention and subsequent endoscopic revision	

Although there is no absolute contraindication for general anesthesia in patients with an ASA score of III-IV, the presence of coronary artery disease or cardiac arrhythmia alone does not determine the choice of anesthetic technique. Particularly in patients with limited cardiovascular reserve, the choice between spinal and general anesthesia should be made on a case-by-case basis. The findings of our study reflect a carefully selected patient group and should not be generalized to all patients with serious systemic disease. Therefore, selecting the appropriate anesthetic method is essential for high-risk spinal surgery cases. As demonstrated in our study, there is a growing need to identify alternative anesthesia strategies for selected patient groups.

Lumbar surgery under awake spinal anesthesia is considered a safe method when performed on appropriately selected patients^(15,22). It has been reported to reduce operative time, length of hospital stay, intraoperative blood loss, postoperative nausea and vomiting, and the need for analgesics^(15,23). Unlike traditional microsurgery, UBE involves continuous saline irrigation throughout the endoscopic procedure; this requires the patient to remain in the prone position without moving for an extended period of time, making it essential to ensure the patient's comfort. Studies on the use of spinal anesthesia during UBE surgery are still limited. However, there are extensive case series evaluating the use of spinal anesthesia, epidural anesthesia, and local anesthesia in monoportal spinal endoscopic surgery⁽²⁴⁻²⁷⁾. In fact, local anesthesia has now become the standard practice in monoportal lumbar disc surgery⁽²⁷⁻³⁰⁾. There are a few studies in the literature reporting that UBELD has been performed under sedation and local anesthesia in elderly and high-risk patients^(16,30). At the same time, studies evaluating cases in which UBELD was administered with epidural and spinal anesthesia are quite rare⁽¹⁶⁾. A distinctive feature of our study is that it includes a selected patient group, employs a multidisciplinary approach to patient selection, and focuses on the spinal anesthesia protocol and perioperative outcomes. However, since the study lacks a control group receiving general or local anesthesia, it is

difficult to assess the superiority or safety of spinal anesthesia compared to other methods.

There are concerns among spinal surgeons regarding the use of spinal anesthesia with UBELD. One of these concerns is that the UBELD surgery may take longer than a traditional approach, during which the sensory block may wear off. Another cause for concern is the potential for disorientation and neural injury due to patient movement during the procedure. Another cause for concern is the possibility that, during spinal anesthesia, an increase in epidural pressure may lead to the flow of irrigation fluid from the site of the dural puncture into the intracranial space, resulting in increased intracranial pressure and a corresponding rise in related complications^(16,30-32). Because the increase in epidural pressure, along with the rise in the level of anesthesia and the risk of causing respiratory depression in the patient, was a cause for concern for us, we were undecided about performing UBELD under spinal anesthesia for an extended period^(30,32). During our planning session with the anesthesia team, to minimize this risk, we positioned the operating table at an approximate vertical tilt 15-20 degrees and used hyperbaric agents to prevent an increase in the level of anesthesia.

In our cases, the saline bags were positioned at a height of 1.7 m to provide gravity-driven irrigation. Except in situations where we have difficulty controlling bleeding due to significant deterioration in visual clarity, we try to complete the surgery without using a manual pump whenever possible to avoid increasing epidural pressure. In the 3 cases where we were required to use a manual pump, albeit rarely to prevent a loss of visual clarity due to bleeding, the patients reported pain in the back of their necks. In this situation, we interpreted the neck pain as a possible clinical warning sign temporarily associated with excessive irrigation pressure. To immediately reduce the irrigation pressure, we extended the fascial incision in the working canal to facilitate the outflow of fluid and paused the irrigation. The patient's neck pain gradually subsided, and the surgery was successfully completed without any further adverse events. No postoperative neck stiffness was observed. This finding has been reported in previous studies involving UBELD performed under sedation and local anesthesia. The authors noted that they paused irrigation, interpreting this as a form of "self-monitoring" of increased epidural pressure⁽³⁰⁾.

In our study, perioperative complications were observed in three patients (13.6%). One patient (4.5%) developed a dural tear. One patient (4.5%) developed a postoperative epidural hematoma. In this patient, the preoperative platelet count, international normalized ratio, and activated partial thromboplastin time were normal. In this case, where the patient was taking aspirin, aspirin administration had not been discontinued during the preoperative period. Six hours after surgery, the patient developed radicular pain without motor deficits. A lumbar magnetic resonance imaging scan performed 10 hours after surgery revealed a spinal epidural hematoma at the surgical site. Since no motor deficits were observed, the patient was closely monitored. Because the pain persisted, a surgical

drainage procedure was performed 24 hours after the initial surgery. The patient was subsequently discharged without any neurological deficits or radicular pain. In one patient (4.5%), urinary retention developed 12 hours after surgery. This patient had benign prostatic hypertrophy. The patient was referred to urology. A urinary catheter was inserted. The patient returned to normal with medical treatment. Although neuraxial anesthesia may have contributed to the urinary retention, the underlying prostate disease and other perioperative factors preclude attributing this event specifically to spinal anesthesia.

When the observed adverse events were evaluated based on their timing and possible mechanisms, the dural tear was determined to be a surgical complication that developed during the procedure. The epidural hematoma, however, developed in the decompression site rather than at the site of the neuraxial puncture and was therefore not specifically attributed to spinal anesthesia. Postoperative urinary retention was considered a multifactorial adverse event due to the patient's preexisting benign prostatic hyperplasia; however, the contribution of spinal anesthesia to this should not be overlooked. In one case, recurrent radicular pain developed one month after surgery, followed by a transforaminal epidural steroid injection due to epidural fibrosis and subsequent endoscopic adhesiolysis. Since this event was not related to the anesthetic technique, it was classified as a delayed postoperative reintervention rather than a perioperative complication. However, the small size of the case series and the absence of a control group do not allow for the exclusion of anesthesia-related complications.

Patient selection is critical for the successful implementation of UBELD under spinal anesthesia. In our opinion, patients scheduled for single- or two-level decompression, for whom the surgical procedure is not expected to be lengthy, and who are able to cooperate are the most suitable candidates. Conversely, we have concerns about administering spinal anesthesia to patients with severe anxiety, those who cannot tolerate the prone position, and those for whom a prolonged surgical procedure is anticipated. Therefore, to optimize perioperative outcomes, we believe that careful preoperative planning between the surgeon and the anesthesiologist is necessary, taking into account the patient's compliance, cognitive status, and social communication skills. In our study, the careful selection of patients played a significant role in the successful completion of procedures under spinal anesthesia without the need to switch to general anesthesia.

Study Limitations

This study has some limitations. The retrospective design of the study poses a risk of selection bias. The sample size is relatively small and consists of a selected group of patients. The fact that the study population included heterogeneous groups and that the groups were small prevented meaningful statistical comparisons from being made. This is not a randomized controlled trial, and there is no control group. Finally, all

procedures were performed by surgeons with four years of UBELD experience who had already completed the learning curve. These findings may not be directly generalizable to centers that are in the early stages of the learning process and have no prior UBELD experience. Another limitation of the study is that the duration of the sensory block and the recovery time were not recorded. The fact that irrigation and epidural pressure were not measured directly is also among the study's limitations.

CONCLUSION

In our study, we observed that UBELD could be performed under spinal anesthesia in a small group of carefully selected ASA III-IV patients, and we completed all procedures without switching to general anesthesia. Perioperative or postoperative adverse events occurred in three patients (13.6%) in this study; however, we believe these were not directly related to spinal anesthesia. In one patient, re-intervention was required 1 month after surgery due to epidural fibrosis. At the three-month follow-up, significant improvements were observed in terms of pain and disability. Our findings should not be interpreted as evidence that spinal anesthesia is safer than general anesthesia, but rather as evidence that spinal anesthesia is feasible in selected patients. The results should not be generalized to all ASA III-IV patients. Although our preliminary findings are encouraging, larger, prospective, and comparative studies are needed to determine the safety and feasibility of routine use of spinal anesthesia in endoscopic lumbar spine surgery for elderly patients and those with high ASA scores.

Ethics

Ethics Committee Approval: This retrospective multicenter study was conducted after obtaining approval for the multicenter study from the Hitit University Faculty of Medicine Institutional Ethics Committee (approval no: 2025-124, date: 03.06.2025).

Informed Consent: Patients who underwent UBELD surgery under spinal anesthesia at two different centers approved by the ethics committee between April 2024 and June 2025 were analyzed retrospectively.

Footnotes

Authorship Contributions

Surgical and Medical Practices: G.K., D.E., M.İ.Ö., Concept: G.K., İ.S., Design: D.E., M.C.E., İ.S., Data Collection or Processing: D.E., A.D., M.C.E., M.İ.Ö., Analysis or Interpretation: A.D., İ.S., Literature Search: D.E., Writing: G.K., D.E., M.C.E.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study received no financial support.

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AGREEMENT BETWEEN ADOLESCENTS, PARENTS, AND AN EXPERT IN VISUAL ASSESSMENTS OF ADOLESCENT POSTURE: AN EXPLORATORY PILOT STUDY

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ABSTRACT

Objective: This exploratory pilot study examined agreement among visual classifications of adolescent posture made by adolescents, parents, and an expert using the same standardized reference images. It also explored whether adolescent-expert agreement differed between adolescents with mild-to-moderate adolescent idiopathic scoliosis (AIS) and healthy controls.

Materials and Methods: Forty adolescents aged 10-18 years (20 with AIS and 20 healthy controls) and one parent per adolescent participated. Adolescents, parents, and one expert independently selected one of five standardized images for each of the following regions: head, shoulders, upper-back, and lumbar/waist. Pairwise and three-rater agreement were assessed using Cohen's κ , Fleiss' κ , and Krippendorff's α . Exact agreement proportions were reported with Wilson 95% confidence intervals (CIs). Region-specific adolescent-parent comparisons were performed using exact McNemar tests with Holm-Bonferroni adjustment for the four regional comparisons. AIS-control comparisons were considered exploratory.

Results: Adolescent-expert agreement ranged from $\kappa=0.30$ to $\kappa=0.43$ and was highest for the head ($\kappa=0.43$, 95% CI, 0.24-0.62). Exact adolescent-expert agreement was 62.5% (95% CI, 47.0-75.8) for the head, 60.0% (44.6-73.7) for the shoulders, and 45.0% (30.7-60.2) for both the upper-back and lumbar/waist regions. Parent-expert agreement ranged from $\kappa=-0.01$ to $\kappa=0.26$, with exact-agreement proportions ranging from 25.0% to 40.0%. Adolescents showed greater exact agreement than parents only in the head region (62.5% vs. 37.5%; $p=0.031$), but this difference did not remain significant after Holm-Bonferroni adjustment (adjusted $p=0.124$). No statistically significant AIS-control differences were detected in total adolescent-expert agreement scores ($p=0.151$) or parent-expert agreement scores ($p=0.306$).

Conclusion: Agreement with the expert's visual classification varied across anatomical regions and was generally moderate. No evidence of equivalence between the AIS and control groups can be inferred from this pilot sample. The findings represent expert-referenced agreement rather than objective recognition accuracy and do not establish the visual approach as valid, reliable, or clinically applicable. Larger studies incorporating multiple assessors, repeated measurements, and independent reference methods are required.

Keywords: Postural self-recognition, postural self-recognition accuracy (PSRA), posture awareness, adolescent, scoliosis, body perception

INTRODUCTION

Adolescence is a critical developmental period during which postural control undergoes substantial reorganization due to rapid skeletal growth accompanied by neurodevelopmental changes^(1,2). During this period, the central nervous system continuously updates the body schema to adapt to changes in body segment proportions. However, rapid skeletal growth and maturation of the body schema do not always occur

synchronously⁽³⁾. This temporary mismatch may alter the processing of proprioceptive information, thereby increasing reliance on visual input for postural control⁽¹⁾. Consequently, postural control during adolescence is more dynamic than in adulthood and is more susceptible to structural and environmental influences^(1,4,5).

One of the principal structural conditions that may affect posture and its perception during adolescence is adolescent idiopathic scoliosis (AIS)^(2,3,5). AIS is a three-dimensional deformity that

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Received: 09.08.2026 **Accepted:** 27.09.2026 **Publication Date:** 14.10.2026

Cite this article as: Bayraktar D, Baykan Çopuroğlu Ö, Er E, Başokçu TO, Öztürk AM. Agreement between adolescents, parents, and an expert in visual assessments of adolescent posture: an exploratory pilot study. J Turk Spinal Surg. 2026;37(4):185-194



extends beyond lateral curvature of the spine in the coronal plane and involves the frontal, sagittal, and transverse planes⁽⁵⁾. This deformity results in visible asymmetries in postural regions, including head position, shoulder level, scapular symmetry, trunk balance, thoracic-pelvic alignment, and waist triangles, leading to noticeable cosmetic changes⁽³⁾. These visible postural alterations may adversely affect adolescents' perception of their physical appearance, psychosocial well-being, and health-related quality of life^(6,7).

Although the effects of AIS on body image have been extensively investigated, body image does not explain whether an adolescent's perception of their posture corresponds to a clinician's visual assessment. Body image refers primarily to the cognitive, affective, and psychological evaluation of physical appearance, whereas body schema represents the sensorimotor representation of body position and configuration. Body awareness is a broader construct involving conscious attention to internal bodily sensations and perceived body position^(3,6,8). Postural self-recognition, as considered in the present study, is related to but conceptually distinct from these constructs because it concerns an adolescent's ability to select a visual representation of their own postural appearance. Current evidence indicates that disturbances in body schema among adolescents with AIS may lead individuals to perceive their own postural alignment differently from clinically or instrumentally assessed alignment^(1-3,6). Patients may overestimate or underestimate the severity of their spinal curvature and may even misperceive the direction of the deformity. These observations suggest that self-perceived posture and clinically assessed posture may not always correspond. Accordingly, examining the agreement between adolescents' visual self-assessments and clinicians' assessments may provide information that is not captured by conventional measures of body image or postural alignment^(1-3,6,8).

Structural spinal deformity can be characterized using radiographic measurements, particularly the Cobb angle, which remains the standard measure of coronal curve magnitude in AIS^(1,5,9). Other clinical and instrumental methods, including photogrammetry, surface topography systems, scoliometry, and standardized postural analysis, can characterize observable features of head, shoulder, trunk, and pelvic alignment⁽¹⁰⁻¹²⁾. However, these methods evaluate structural or externally observable postural characteristics and do not directly determine whether adolescents identify their own postural appearance in the same way as a clinician. Moreover, a clinician's visual classification should not itself be regarded as an objective gold standard because it may be influenced by observer judgment and measurement error.

Patient-reported instruments used in AIS assess several related but distinct outcomes. Measures of body image and health-related quality of life primarily capture psychological responses, satisfaction, functional impact, and concerns related to appearance. Visual instruments such as the Walter Reed visual assessment scale (WRVAS) and the spinal appearance

questionnaire (SAQ) use standardized drawings to evaluate the perceived type or severity of spinal and trunk deformity^(13,14). The WRVAS focuses on perceived deformity across features such as spinal curvature, rib and flank prominence, trunk imbalance, and shoulder or scapular asymmetry, whereas the SAQ combines visual representations with questions concerning spinal appearance. These established instruments provide valuable information about perceived deformity and appearance but were not designed specifically to quantify exact categorical agreement among an adolescent, a parent, and a clinician using the same region-specific visual categories.

To address this methodological gap, the present study used a standardized visual reference approach in which adolescents, parents, and an expert assessor independently selected the image that they believed best represented the adolescent's posture in each anatomical region. The resulting outcome was interpreted as expert-referenced postural self-recognition agreement rather than objective perceptual accuracy. It represented concordance between the adolescent's self-classification and the expert's visual classification using the same image set and was not interpreted as validation against an independent objective reference standard. Parent-expert and adolescent-parent agreement were examined as separate forms of concordance.

The primary aim of this exploratory pilot study was to provide a preliminary examination of agreement between adolescents' self-selected visual representations of their posture and an expert's classifications using the same standardized visual reference set. The secondary aims were to evaluate parent-expert and adolescent-parent agreement, compare region-specific adolescent-expert and parent-expert exact-agreement proportions, and explore whether adolescent-expert agreement differed between adolescents with mild-to-moderate AIS and healthy controls. We hypothesized that adolescent-expert agreement would be greater than parent-expert agreement in at least one anatomical region and that the magnitude of agreement would vary across anatomical regions. Given the exploratory nature and limited sample size of the study, the comparison between the AIS and control groups was considered hypothesis-generating, and no assumption of equivalence between the groups was made.

MATERIALS AND METHODS

Study Design and Participants

This exploratory cross-sectional methodological pilot study was conducted to provide a preliminary examination of a visual reference-based assessment approach developed for examining agreement between adolescents' self-assessments and an expert's visual classification of their posture. The study was conducted in the Department of Orthopedics and Traumatology at Ege University between March and July 2026. The study was conducted in accordance with the Declaration

of Helsinki, and the study protocol was approved by the Ege University Faculty of Medicine Ethics Committee (approval no: 26-3T/2, date: 05.03.2026). Voluntary assent was obtained from all adolescents, and written informed consent was obtained from their parents.

Adolescents with AIS and healthy controls were recruited consecutively from the Department of Orthopedics and Traumatology at Ege University during the study period. Adolescents with AIS were recruited during their clinical assessments, whereas healthy adolescents without a known diagnosis of scoliosis or another spinal deformity were recruited from the same department during the study period. No individual matching was performed; healthy controls were enrolled within the same predefined age range as the AIS group.

The AIS group included adolescents aged 10-18 years who had been diagnosed with AIS by an orthopedic specialist, whose scoliosis had been confirmed on standing spinal radiographs, who had sufficient cognitive ability to understand the study instructions, and who voluntarily agreed to participate. The ability to understand the study instructions was determined clinically by the researchers during the initial interview, based on each adolescent's ability to understand and appropriately follow the verbal instructions provided for the assessment. The healthy control group consisted of adolescents within the same age range who had no known scoliosis or spinal deformity and no musculoskeletal disorder limiting activities of daily living.

The exclusion criteria for both groups included neurological disorders, congenital spinal anomalies, previous spinal surgery, and the presence of rheumatological, neuromuscular, or systemic diseases that could substantially affect posture. Conditions affecting the ability to understand or complete the visual assessment were also considered exclusion criteria.

Parents were eligible if they were the adolescent's mother or father, were literate, were able to read and understand Turkish, and voluntarily agreed to participate. Parents with cognitive impairment, a history of psychiatric disorders interfering with communication, or visual or reading problems that could prevent completion of the assessment form were excluded. The relationship of the participating parent to the adolescent was recorded as mother or father.

Because this was an exploratory pilot study evaluating a newly developed visual classification approach, no formal a priori power calculation was performed. A pragmatic target of 20 adolescents per group was established based on the feasibility of recruitment during the predefined study period. Accordingly, the study was not powered to demonstrate equivalence between the AIS and healthy control groups.

Development of the Visual Posture Assessment Tool

A region-specific visual assessment tool was developed to enable adolescents to evaluate their own posture using standardized visual references. The development of the visual classification approach was based on regional characteristics

of postural alignment that are readily observable by individuals and are commonly considered during clinical postural assessment. Accordingly, the assessment was structured around four postural regions: head, shoulders, upper-back, and lumbar/waist region. The clinical characteristics to be depicted were determined by researchers with experience in physiotherapy, orthopedics, and postural assessment, and the illustrations were digitally produced and graphically standardized in collaboration with a visual communication design specialist.

For each region, five standardized visual reference images representing different postural appearances were created. The use of five alternatives was intended to represent a sufficiently broad range of visually distinguishable postural configurations while maintaining a manageable number of response options for adolescents. Rather than requiring participants to describe their posture verbally, the assessment was designed to allow them to select the image they believed best represented their own posture. The same standardized visual reference set was used for adolescent, parent, and expert assessments, thereby enabling direct comparison among the three evaluations.

Within each image set, the response alternatives were coded a-e from left to right. In the head set, image a depicted an approximately neutral head position; images b and c depicted left-sided lateral head inclination at different magnitudes; and images d and e depicted right-sided lateral head inclination at different magnitudes. In the shoulder set, image a depicted approximately level shoulders; images b and c represented left-sided shoulder-height asymmetry at different magnitudes; and images d and e represented right-sided shoulder-height asymmetry at different magnitudes. In the upper-back set, images a-e depicted progressively increasing sagittal trunk curvature and thoracic kyphotic appearance, with image a representing the least pronounced and image e the most pronounced configuration. Similarly, in the lumbar/waist set, images a-e depicted progressively increasing lumbar curvature and lordotic appearance, with image a representing the least pronounced and image e the most pronounced configuration.

All illustrations were standardized with respect to body position, viewing perspective, figure dimensions, clothing, background, and graphical style; only the postural characteristic targeted by the relevant image set was systematically varied. Identical visual reference images were incorporated into the adolescent and parent assessment forms, which are provided in Supplementary Files 1 and 2, respectively.

The present visual approach differs from the WRVAS and the SAQ, which primarily assess perceived scoliosis-related trunk deformity and appearance severity^(13,14). The current approach uses the same region-specific images for independent classifications by the adolescent, parent, and expert and evaluates exact concordance among these classifications. It was not designed to assess body-image satisfaction, health-related quality of life, or radiographic deformity severity.

Before implementation, the visual reference images underwent quantitative content evaluation and qualitative review by an

expert panel, as described below. The final visual reference set was established after consideration of the experts' ratings and written feedback.

Content Evaluation by Experts

The content of the developed visual assessment tool was reviewed by a panel of 10 experts with experience in posture and musculoskeletal assessment, including five physiotherapists and five orthopedic and traumatology specialists. Each expert independently evaluated every image for relevance, clarity, and representativeness using a four-point scale: 1, not appropriate; 2, appropriate only after major revision; 3, appropriate with minor revision; and 4, highly appropriate. Ratings of 3 or 4 were considered acceptable. Experts were also invited to provide written comments and revision recommendations for each image.

Content validity was quantified using the item-level content validity index (I-CVI), calculated as the proportion of experts who assigned a rating of 3 or 4 to each image. For a panel of 10 experts, an I-CVI of ≥ 0.78 was considered acceptable⁽¹⁵⁾. Scale-level content validity was evaluated using both the average method (S-CVI/Ave) and universal-agreement method (S-CVI/UA), with an S-CVI/Ave of ≥ 0.90 considered acceptable⁽¹⁵⁾. The S-CVI/Ave was calculated as the mean of the I-CVI values across all 20 images, whereas the S-CVI/UA represented the proportion of images that received acceptable ratings from all experts. All 20 images received acceptable ratings from all 10 experts; consequently, the I-CVI was 1.00 for every image, and both the S-CVI/Ave and S-CVI/UA were 1.00. Thus, unanimous expert agreement was achieved for all images. As the experts did not identify any image requiring modification, no revisions were made following the content evaluation. These indices reflect the experts' judgments of the relevance, clarity, and representativeness of the images; they indicate expert-rated content appropriateness and do not constitute evidence of construct or criterion validity.

Assessment Procedure

Data were collected through face-to-face assessment sessions with the adolescents and their parents. Before data collection, standardized verbal instructions were provided without directing participants toward any particular image. The age and sex of each adolescent were recorded, and, for the AIS group, Cobb-angle data were obtained from standing spinal radiographs available in the medical records. Parent age and education level were also recorded.

The visual assessment tool was administered separately for the four postural regions (head, shoulders, upper-back, and lumbar/waist region). For each region, adolescents were presented with five standardized visual reference images and were asked to select the image they believed best represented their own posture. Parents were asked to use the same standardized visual reference set to select, for each region, the image they believed best represented their adolescent's posture. Adolescents and

parents completed their assessments separately and were not permitted to view or discuss each other's selections. No feedback regarding the selections was provided until all assessments had been completed.

The expert assessment was performed through direct observation of the adolescent's posture using the same standardized visual reference set. The expert assessor was a physiotherapist with 20 years of clinical experience in postural assessment and AIS management. The assessor routinely evaluated adolescents with postural and spinal disorders in clinical practice. Adolescents were assessed barefoot in their habitual standing posture in a well-lit clinical room. Posture was observed from posterior and lateral perspectives corresponding to the perspectives depicted in the visual reference images. The expert independently selected the image that most closely represented the adolescent's posture in each anatomical region. The expert assessor was not involved in the development or content evaluation of the visual reference images.

Adolescent, parent, and expert assessments were conducted independently to prevent the evaluators from being influenced by one another's selections. The expert was blinded to the image selections made by the adolescents and parents. However, the expert was not considered blinded to AIS/control status because visible postural characteristics could indicate the presence of scoliosis. The selected image for each region was recorded as a categorical code.

The expert's visual classification was used as a clinical comparator rather than an objective or independently validated reference standard. Exact correspondence between the adolescent's and expert's selections was defined as adolescent-expert agreement, whereas correspondence between the parent's and expert's selections was defined as parent-expert agreement. Accordingly, these outcomes represent agreement with one clinical observer rather than objective recognition accuracy. Because each participant was assessed once by a single expert, intra-rater and inter-rater reliability of the expert classifications could not be evaluated.

Operational Definition and Assessment of Agreement Outcomes

In the present study, adolescent-expert agreement was operationally defined as the exact correspondence between the image an adolescent believed best represented their own posture and the image selected by the expert based on direct observation. This outcome was interpreted as agreement with the expert's visual classification rather than accuracy against an objective gold standard. Within the visual assessment tool, each postural region was assigned a numerical identifier, while the five visual reference options for each region were coded using the letters a-e (e.g., 1b). Exact agreement was defined as the adolescent and the expert selecting the same image code for a given postural region and was coded as 1; any difference between the selected image codes was coded as 0.

Adolescent-expert agreement was evaluated separately for the head, shoulders, upper-back, and lumbar/waist region. For

each region, the image code selected by the adolescent was compared with the code selected by the expert to determine whether exact agreement was present. The same procedure was applied to the parent assessments by comparing the image code selected by the parent with that selected by the expert; this outcome was evaluated separately as parent-expert agreement. Adolescent-parent agreement was also assessed by comparing their respective image selections for each region. For each adolescent and parent, a total expert-agreement score was calculated by summing the number of anatomical regions in which their selected image corresponded exactly to the expert's selection. The total score ranged from 0 to 4, with higher scores indicating exact agreement with the expert across a greater number of regions. This total score was used as a participant-level summary of regional agreement and was not interpreted as a validated measurement scale.

Statistical Analysis

Analyses were performed using IBM SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA). Because Fleiss' κ and Krippendorff's α are not implemented in this version of the software, these two coefficients were calculated directly from the raw rating matrices using their standard formulae for nominal data, and all reported values were verified by independent recomputation. Descriptive statistics are presented as mean and standard deviation for continuous variables, median and range for ordinal variables, and number and percentage for categorical variables. Total expert-agreement scores are presented as median [interquartile range (IQR)] together with mean and standard deviation.

The image codes were analyzed primarily as categorical responses because the principal outcome was exact correspondence between the images selected by different raters. Pairwise agreement between the adolescent and the expert, between the parent and the expert, and between the adolescent and the parent was quantified separately for each postural region using unweighted Cohen's κ . Agreement among the adolescent, parent, and expert was quantified using Fleiss' κ and Krippendorff's α . Ninety-five percent confidence intervals (CIs) for all agreement coefficients were estimated using a non-parametric bootstrap procedure in which participants, each contributing an adolescent, parent, and expert classification, were resampled with replacement (2,000 resamples; percentile method)⁽¹⁶⁾. Interpretation focused primarily on the magnitude of the agreement coefficients rather than their statistical significance.

The head and shoulder image sets included direction-specific configurations combining the side and magnitude of postural deviation and were therefore treated as nominal categories. The upper-back and lumbar/waist image sets depicted progressively changing sagittal postural configurations and had an ordinal structure. Nevertheless, unweighted κ was retained as the primary agreement coefficient because the prespecified outcome required exact selection of the same image, and

any non-identical selection was classified as disagreement regardless of the proximity of the two images. Unweighted κ therefore deliberately treats all disagreements as equivalent: in the upper-back and lumbar/waist sets, a discrepancy between adjacent images (e.g., b vs. c) and a discrepancy between the two extreme images (a vs. e) contribute equally to disagreement. Consequently, the coefficients for these regions quantify exact concordance only and do not reflect the degree of approximate correspondence between raters.

Exact-agreement proportions were defined as the percentages of adolescents or parents whose selected image corresponded exactly to the expert's selection. Given the small sample size, 95% CIs for these proportions were calculated using the Wilson score method rather than the normal approximation.

Region-specific differences between adolescent-expert and parent-expert exact-agreement proportions were examined using paired McNemar tests, with exact binomial p-values reported when appropriate. The four regional observations contributed by each adolescent-parent pair were neither pooled nor treated as statistically independent observations for inferential analysis. Overall exact-agreement frequencies across the four anatomical regions were summarized descriptively only, and no inferential test was applied to the pooled regional observations. This approach preserved the paired structure of the region-specific comparisons and avoided pseudoreplication arising from multiple regional observations contributed by the same participant. Because four region-specific tests were performed for this comparison, the analyses were considered exploratory, and p-values were additionally adjusted for multiplicity using the Holm-Bonferroni procedure⁽¹⁷⁾. Both nominal and adjusted p-values are reported.

Differences between the AIS and control groups were examined using Fisher's exact test for region-specific exact-agreement proportions and the Mann-Whitney U test for total expert-agreement scores. Because the primary outcome was exact categorical agreement and the total agreement score was a bounded ordinal score derived from four dichotomous comparisons, normality was neither assumed nor formally tested; given the small sample size, non-parametric tests were used throughout. The AIS-control analyses were considered exploratory and were not interpreted as tests of group comparability or equivalence. Their nominal p-values are reported without adjustment for multiplicity.

The dataset was complete for all adolescent, parent, and expert image selections, and no imputation was required. All tests were two-tailed, and statistical significance was set at $p < 0.05$.

RESULTS

Participant Characteristics

A total of 40 adolescents (20 with AIS and 20 healthy controls) and one parent for each adolescent were included. The mean adolescent age was 13.6 ± 2.3 years. In the AIS group, the mean

Cobb angle was $24.9 \pm 6.7^\circ$, with values ranging from 10° to 30° . No statistically significant between-group differences were detected in adolescent age, parental age, or parental education level. Although the difference in sex distribution did not reach statistical significance, females predominated in the control group, whereas males predominated in the AIS group (Table 1).

Adolescent-expert Agreement

Adolescent-expert agreement was highest for the head region ($\kappa=0.43$, 95% CI 0.24-0.62) and ranged from $\kappa=0.30$ to $\kappa=0.43$ across the four anatomical regions. The magnitude of these coefficients indicated fair-to-moderate rather than strong agreement, and the wide CIs indicate that these estimates were imprecise (Table 2). The proportion of exact adolescent-expert agreement was 62.5% for the head, 60.0% for the shoulders, and 45.0% for both the upper-back and lumbar/waist regions (Table 3).

Parent-expert Agreement

Parent-expert κ coefficients ranged from -0.01 for the upper-back region to 0.26 for the lumbar/waist region, indicating generally limited agreement with the expert; the 95% CIs for the head, shoulder, and upper-back coefficients included zero (Table 2). Parent-expert exact-agreement proportions ranged from 25.0% for the upper-back region to 40.0% for the lumbar/waist region (Table 3).

Comparison of Expert-referenced Agreement Between Adolescents and Parents

Across the four regions, adolescents selected the same image as the expert in 85 of 160 classifications (53.1%), whereas parents selected the same image as the expert in 56 of 160 classifications (35.0%). These pooled values are presented descriptively only because the four regional classifications contributed by each participant were not statistically independent.

Table 1. Participant characteristics by study group

Variable	Control (n=20)	AIS (n=20)	Total (n=40)
Sample size, n	20	20	40
Age of adolescents, years, mean (SD)	13.5 (2.3)	13.7 (2.3)	13.6 (2.3)
Sex (female/male), n	13/7	7/13	20/20
Cobb angle ($^\circ$), mean (SD)	-	24.9 (6.7)	24.9 (6.7)
Cobb angle, range ($^\circ$)	-	10-30	10-30
Age of parents, years, mean (SD)	45.4 (5.7)	45.7 (4.5)	45.5 (5.1)
Parental education, median (range)	3.5 (1-5)	3 (1-5)	3 (1-5)

Between-group comparisons were performed using the Mann-Whitney U test for adolescent age, parental age, and parental education level, and Fisher's exact test for sex distribution. Parental education was classified as: 1, primary school; 2, secondary school; 3, high school; 4, university; and 5, postgraduate education. -, not applicable. AIS: Adolescent idiopathic scoliosis, SD: Standard deviation

Table 2. Pairwise and multi-rater agreement across anatomical regions

Anatomical region	Adolescent-expert Cohen's κ (95% CI)	Parent-expert Cohen's κ (95% CI)	Adolescent-parent Cohen's κ (95% CI)	Fleiss' κ (95% CI)	Krippendorff's α (95% CI)
Head	0.43 (0.24, 0.62)	0.13 (-0.09, 0.33)	0.14 (-0.09, 0.37)	0.22 (0.07, 0.37)	0.23 (0.08, 0.37)
Shoulders	0.37 (0.13, 0.58)	0.11 (-0.08, 0.30)	-0.05 (-0.19, 0.10)	0.13 (0.00, 0.25)	0.14 (0.01, 0.26)
Upper-back	0.30 (0.11, 0.49)	-0.01 (-0.18, 0.16)	-0.04 (-0.18, 0.12)	0.08 (-0.04, 0.18)	0.08 (-0.03, 0.19)
Lumbar/waist	0.32 (0.15, 0.50)	0.26 (0.09, 0.44)	0.35 (0.13, 0.56)	0.30 (0.13, 0.45)	0.30 (0.14, 0.46)

Pairwise agreement was evaluated using unweighted Cohen's κ , and three-rater agreement was evaluated using Fleiss' κ and Krippendorff's α . Unweighted coefficients represent exact categorical agreement; any selection of different image codes was classified as disagreement. Interpretation focused on the magnitude of the coefficients rather than statistical significance alone. 95% confidence intervals (CIs) were obtained by non-parametric bootstrap resampling of participants (2,000 resamples, percentile method). κ : Kappa coefficient

Table 3. Exact agreement with the expert according to anatomical region

Anatomical region	Adolescent-expert exact agreement, n (%)	Wilson 95% CI	Parent-expert exact agreement, n (%)	Wilson 95% CI
Head	25 (62.5)	47.0-75.8	15 (37.5)	24.2-53.0
Shoulders	24 (60.0)	44.6-73.7	15 (37.5)	24.2-53.0
Upper-back	18 (45.0)	30.7-60.2	10 (25.0)	14.2-40.2
Lumbar/waist	18 (45.0)	30.7-60.2	16 (40.0)	26.3-55.4

Exact agreement was defined as selection of the same visual category as the expert. Confidence intervals (CIs) were calculated using the Wilson score method

In the region-specific paired analyses, adolescent-expert exact agreement was more frequent than parent-expert exact agreement for the head region at the nominal level (62.5% vs. 37.5%; exact McNemar $p=0.031$); however, this difference was not statistically significant after Holm-Bonferroni adjustment for the four regional comparisons (adjusted $p=0.124$). No statistically significant differences were detected for the shoulders ($p=0.078$; adjusted $p=0.234$), upper-back ($p=0.115$; adjusted $p=0.234$), or lumbar/waist region ($p=0.727$; adjusted $p=0.727$) (Table 4).

Multi-rater Agreement Among Adolescents, Parents, and the Expert

Three-rater agreement varied across anatomical regions. Fleiss' κ was highest for the lumbar/waist region ($\kappa=0.30$) and lowest for the upper-back region ($\kappa=0.08$). Krippendorff's α demonstrated a similar pattern, ranging from 0.08 for the upper-back to 0.30 for the lumbar/waist region (Table 2). Overall, the magnitudes of the coefficients indicated limited multi-rater agreement.

Exploratory Comparison Between the AIS and Control Groups

The total adolescent-expert agreement score was median 3 (IQR 1-4) (mean 2.45 ± 1.39) in the control group and median

2 (IQR 0.25-3) (mean 1.80 ± 1.44) in the AIS group. However, no statistically significant between-group difference was detected in this pilot sample ($U=148$, $p=0.151$). The corresponding parent-expert agreement scores were median 1 (IQR 1-2) (mean 1.25 ± 0.79) and median 2 (IQR 1-2) (mean 1.55 ± 1.05), respectively, with no statistically significant difference ($U=164$, $p=0.306$). Region-specific analyses similarly detected no statistically significant differences between the AIS and control groups (Table 5). These findings should not be interpreted as demonstrating equivalence between the groups.

DISCUSSION

This exploratory pilot study provided an initial evaluation of agreement among adolescents', parents', and one expert's visual classifications of adolescent posture using the same standardized reference images. Adolescent-expert agreement was greatest for the head region and ranged from fair to moderate across the four anatomical regions. Parent-expert and adolescent-parent agreement was generally limited, although the magnitude of agreement varied by region. The proportion of classifications corresponding exactly to the expert's selection was numerically higher for adolescents than

Table 4. Region-specific comparison of exact agreement with the expert between adolescents and parents

Anatomical region	Adolescent only in agreement, n	Parent only in agreement, n	McNemar χ^2	Exact p-value	Holm-adjusted p-value
Head	14	4	4.500	0.031	0.124
Shoulders	15	6	3.048	0.078	0.234
Upper-back	14	6	2.450	0.115	0.234
Lumbar/waist	5	3	0.125	0.727	0.727

Values represent discordant adolescent-parent pairs within each anatomical region. McNemar χ^2 values are continuity-corrected; p-values are exact (binomial). Holm-Bonferroni adjustment was applied across the four regional comparisons, and these analyses were exploratory. No overall McNemar test was conducted by pooling regional observations because this would violate the assumption of independent paired observations

Table 5. Exploratory comparison of expert-referenced agreement between the AIS and control groups

Anatomical region	Rater	Control, n (%)	AIS, n (%)	p-value
Head	Adolescent	15 (75.0)	10 (50.0)	0.191
Shoulders	Adolescent	14 (70.0)	10 (50.0)	0.333
Upper-back	Adolescent	11 (55.0)	7 (35.0)	0.341
Lumbar/waist	Adolescent	9 (45.0)	9 (45.0)	1.000
Head	Parent	9 (45.0)	6 (30.0)	0.514
Shoulders	Parent	7 (35.0)	8 (40.0)	1.000
Upper-back	Parent	3 (15.0)	7 (35.0)	0.273
Lumbar/waist	Parent	6 (30.0)	10 (50.0)	0.333
Overall [†]	Adolescent	3 (1-4) 2.45 (1.39)	2 (0.25-3) 1.80 (1.44)	$U=148$; 0.151
Overall [†]	Parent	1 (1-2) 1.25 (0.79)	2 (1-2) 1.55 (1.05)	$U=164$; 0.306

Regional values represent the number and percentage of participants whose selected image corresponded exactly to the expert's selection. Region-specific comparisons were performed using two-sided Fisher's exact tests. [†]: Overall values represent the total expert-agreement score (range 0-4), presented as median (interquartile range) and mean (standard deviation), and were compared using the Mann-Whitney U test. These exploratory analyses were not interpreted as tests of group equivalence, AIS: Adolescent idiopathic scoliosis

for parents in each of the four regions; however, a nominally significant region-specific difference was observed only for the head, and this difference did not remain statistically significant after adjustment for multiple comparisons. Accordingly, the hypothesis that adolescent-expert agreement would exceed parent-expert agreement in at least one anatomical region was not supported after correction for multiplicity. Because the pooled regional observations were not subjected to inferential analysis, no conclusion was drawn regarding an overall difference between adolescents and parents. Furthermore, no statistically significant difference in expert-referenced agreement was detected between adolescents with mild-to-moderate AIS and healthy controls in this pilot sample. These findings should be regarded as preliminary and hypothesis-generating rather than evidence that the visual approach is a validated clinical measurement instrument.

Recognition of one's own posture is a complex perceptual process involving the integration of visual, proprioceptive, and somatosensory information within the central nervous system^(2,6,8,18). Related aspects of body perception have traditionally been conceptualized through body awareness, body schema, and body image^(3,6,8,19). Body image primarily concerns the cognitive, emotional, and psychological evaluation of physical appearance, whereas body schema refers to the sensorimotor representation of body position and configuration. Body awareness encompasses conscious attention to bodily sensations and perceived body position. The outcome examined in the present study differs from these constructs because it represents exact agreement between an adolescent's visual self-classification and one expert's visual classification using the same image set. It should therefore be interpreted as expert-referenced postural self-recognition agreement, not as an objective measure of perceptual accuracy. The magnitude of adolescent-expert agreement varied across anatomical regions, with the highest coefficient observed for the head and lower coefficients for the upper-back and lumbar/waist regions. One possible explanation is that the head and shoulders are encountered more frequently through mirrors, photographs, and interpersonal interactions and may therefore provide more accessible visual cues^(6,8,20,21). In contrast, the upper-back and lumbar/waist regions are not directly visible during routine activities, and their perception may depend more strongly on proprioceptive and somatosensory information^(6,7,18,20). Previous research suggests that body representation may be facilitated when visual and proprioceptive information can be integrated^(6,8,19,20). Nevertheless, the present study did not directly measure visual exposure, proprioception, or the mechanisms underlying regional differences. Consequently, these explanations remain hypotheses and should not be interpreted as mechanisms demonstrated by the current findings.

Parent-expert agreement was generally limited, ranging from $\kappa=-0.01$ for the upper-back region to $\kappa=0.26$ for the lumbar/waist region. Previous studies have mainly compared parental

perceptions of adolescents' appearance or spinal deformity with adolescents' self-perceptions and have sometimes reported similarities between these perspectives^(6,13,22). However, parent-adolescent agreement does not necessarily imply correspondence with a clinician's visual classification. In the present study, adolescents demonstrated numerically higher exact-agreement proportions than parents, but the region-specific difference reached nominal significance only for the head and did not persist after multiplicity adjustment. Therefore, the findings do not support a broad conclusion that adolescents consistently classify their posture better than their parents. Rather, they suggest that adolescent, parent, and expert classifications may provide different perspectives and that the magnitude of concordance depends on the anatomical region being evaluated.

The three-rater coefficients also indicated region-dependent variation. Fleiss' κ and Krippendorff's α were highest for the lumbar/waist region and lowest for the upper-back region, although their overall magnitudes remained limited. These coefficients reflect simultaneous classification by the adolescent, parent, and expert and therefore address a different question from pairwise agreement. The findings illustrate the potential value of reporting both pairwise and multi-rater coefficients; however, statistical significance should not be interpreted as evidence of clinically strong agreement, particularly in a small pilot sample⁽²³⁾.

No statistically significant difference in adolescent-expert agreement was detected between the AIS and healthy control groups. Previous research found no differences in the perception of vertical and horizontal orientation between adolescents with idiopathic scoliosis and healthy controls⁽²⁴⁾, whereas other studies suggested that discrepancies in perceived trunk appearance may become more apparent with increasing curve magnitude and may be less evident in milder deformities^(1,3). Similarly, body image may be affected in adolescents with mild AIS even when subjective trunk appearance is not strongly associated with radiographic or photogrammetric measurements⁽²⁵⁾. The adolescents with AIS in the present study had Cobb angles ranging from 10° to 30°, and the restricted severity range may have limited the ability to detect group differences. Moreover, the small sample provided limited statistical power. Thus, the findings indicate only that no statistically significant between-group difference was detected; they do not demonstrate that adolescents with AIS and healthy adolescents have equivalent postural self-recognition.

The sex distribution should also be considered when interpreting the exploratory group comparison. Females predominated in the control group, whereas males predominated in the AIS group. Although this difference was not statistically significant, the distributions were notably different in direction, and sex-related differences in attention to appearance or body perception could have influenced the findings. Because of the small sample, sex-adjusted or sex-stratified analyses were not feasible. The AIS-control results should therefore be interpreted

cautiously and examined in larger samples with more balanced sex distributions.

Existing AIS-related patient-reported measures primarily address body image, perceived deformity, trunk appearance, psychosocial effects, and health-related quality of life^(3,6,26-28). Instruments such as the WRVAS and the SAQ use visual representations to assess perceived scoliosis-related deformity and appearance^(13,14). These measures provide clinically important information but do not specifically quantify exact agreement among adolescents, parents, and a clinician using the same set of region-specific visual alternatives. The approach examined in the present study addresses this narrower question of cross-observer concordance. It is not intended to replace existing measures of body image, perceived deformity, trunk aesthetics, body awareness, or health-related quality of life. At this stage, it should be considered a preliminary visual classification approach whose potential clinical value remains to be established.

Study Limitations

Several limitations should be considered. First, this exploratory pilot study included only 40 adolescent-parent pairs, and no formal a priori power calculation was performed. The study may therefore have been insufficiently powered to detect meaningful differences, particularly between the AIS and control groups. The small sample also resulted in wide CIs for the agreement coefficients, so the regional estimates should be regarded as imprecise. Furthermore, the overall adolescent-parent frequencies were summarized descriptively because pooling the four regional observations for inferential analysis would have violated the independence assumption. Consequently, no inferential conclusion regarding an overall adolescent-parent difference can be drawn from this study. Second, the AIS sample was restricted to mild-to-moderate deformities with Cobb angles of 10°-30°, limiting generalizability to adolescents with more severe curves. Third, the expert's visual classification was used as the comparator, but it was not independently validated against radiography, photogrammetry, surface topography, or another objective postural reference. The expert assessment may itself have contained classification error. Fourth, each participant was assessed once by a single expert; consequently, intra-rater and inter-rater reliability could not be determined. Fifth, the expert-based content evaluation established the content appropriateness of the images only; the reliability, construct validity, criterion validity, responsiveness, and clinically meaningful interpretation of the visual approach have not yet been established. In addition, because unweighted κ was used for the ordinal upper-back and lumbar/waist image sets, near-miss classifications were counted as full disagreements; the reported coefficients may therefore understate approximate correspondence in these regions. Sixth, the imbalance in sex distribution may have confounded the AIS-control comparison. Seventh, current or previous brace treatment, physiotherapy, and scoliosis-specific exercise may influence postural awareness;

the small sample did not permit these potential effects to be examined adequately. Finally, the cross-sectional design precluded assessment of temporal stability or responsiveness to postural education and rehabilitation. Future studies should include larger and more diverse samples, multiple blinded assessors, repeated assessments, independent instrumental reference measures, and prospective evaluation of reliability, validity, and responsiveness before clinical application is considered.

CONCLUSION

This exploratory pilot study demonstrated that adolescents', parents', and an expert's visual classifications of adolescent posture can be compared using the same standardized reference image set. Adolescent-expert agreement varied across anatomical regions and was greatest for the head, whereas parent-expert agreement was generally limited. Although exact-agreement proportions were numerically higher for adolescents than for parents in all four regions, the only nominally significant difference, observed for the head, did not remain significant after adjustment for multiple comparisons and should be interpreted with caution. No statistically significant difference in adolescent-expert agreement was detected between adolescents with mild-to-moderate AIS and healthy controls; however, this finding should not be interpreted as evidence of equivalence. The present findings provide preliminary evidence regarding expert-referenced visual agreement and do not establish the approach as a valid, reliable, or clinically applicable measurement instrument. Larger studies incorporating multiple assessors, repeated assessments, and independent objective reference measures are required to determine its reliability, validity, responsiveness, and potential clinical utility.

Ethics

Ethics Committee Approval: The study protocol was approved by the Ege University Faculty of Medicine Ethics Committee (approval no: 26-3T/2, date: 05.03.2026).

Informed Consent: Voluntary assent was obtained from all adolescents, and written informed consent was obtained from their parents.

Acknowledgments

The authors wish to thank the adolescents and their parents who voluntarily participated in this study. The authors also wish to thank the physiotherapists and orthopedic specialists who contributed to the content evaluation of the visual assessment tool.

Footnotes

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist with English translation, language editing, and improvement of the clarity and readability of the manuscript. The tool was not used for data collection, statistical

analysis, generation of study results, or independent scientific interpretation. All AI-assisted text was critically reviewed, revised, and approved by the authors, who take full responsibility for the scientific content and integrity of the manuscript.

Authorship Contributions

Surgical and Medical Practices: D.B., Concept: D.B., Ö.B.Ç., E.E., T.O.B., A.M.Ö., Design: D.B., Ö.B.Ç., E.E., T.O.B., A.M.Ö., Data Collection or Processing: D.B., Ö.B.Ç., E.E., A.M.Ö., Analysis or Interpretation: T.O.B., Literature Search: D.B., Writing: D.B., Ö.B.Ç., E.E., T.O.B., A.M.Ö.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study received no financial support.

Supplementary File Link: <https://d2v96fxpocvxx.cloudfront.net/bda9171a-fae8-4995-8276-2138323f1e16/content-images/eabdc531-f967-4eb7-8523-ceab4ba8216b.pdf>

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REAL-TIME MULTIMODAL NEUROMONITORING DURING UNILATERAL BIPORTAL ENDOSCOPIC LUMBAR SURGERY: A SINGLE-CENTER SAFETY ANALYSIS

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ABSTRACT

Objective: Lumbar discectomy and decompression using unilateral biportal endoscopy (UBE) have become increasingly adopted minimally invasive techniques in spine surgery. Nevertheless, intraoperative neural irritation may occur due to procedure-related factors and the technical learning curve. This study aimed to describe intraoperative electrophysiological findings obtained with multimodal neuromonitoring during lumbar surgery performed using UBE, with particular attention to free-running electromyographic activity associated with electrocautery use.

Materials and Methods: A retrospective analysis was performed on 78 patients who underwent lumbar discectomy or decompression using UBE between January 2024 and June 2025. The multimodal intraoperative neuromonitoring (IONM) protocol consisted of free-running electromyography (freeEMG), motor evoked potentials (MEP), and somatosensory evoked potentials (SEP).

Results: FreeEMG activity temporally associated with electrocautery use was observed in 32 of 78 patients (41.0%). In these cases, the electrocautery power was reduced intraoperatively, after which the freeEMG activity returned to baseline. Among 18 patients with preoperative motor weakness, postoperative improvement was observed in 14. No new postoperative neurological deficits were identified.

Conclusion: Multimodal IONM provided real-time electrophysiological information during lumbar surgery performed using UBE. FreeEMG activity was observed in temporal association with electrocautery use and returned to baseline after modification of the electrocautery settings. These findings are descriptive and do not establish a protective effect of IONM. Prospective controlled studies are needed to determine whether such intraoperative feedback translates into improved neurological outcomes.

Keywords: Unilateral biportal endoscopy, intraoperative neuromonitoring, freeEMG, motor evoked potentials, somatosensory evoked potentials

INTRODUCTION

Lumbar surgery using unilateral biportal endoscopy (UBE) has become an increasingly preferred minimally invasive treatment option for lumbar degenerative disorders because of smaller incisions, reduced soft tissue injury, and favorable postoperative recovery profile. However, intraoperative and postoperative complications may still occur, particularly due to the technical learning curve associated with UBE and the increasing number of elderly patients presenting with degenerative spinal pathology related to prolonged life expectancy⁽¹⁻³⁾. The close proximity of surgical instruments to neural structures, limitations inherent to endoscopic visualization, and potential thermal irritation or injury associated with coagulation devices may further increase the risk of complications^(1,2,4,5). Therefore, the development and implementation of intraoperative safety

strategies during procedures using UBE remain of considerable importance^(1,6).

Intraoperative neuromonitoring (IONM) is widely used in spinal surgery to establish baseline neurological function at the beginning of surgery and to detect intraoperative changes in neural integrity^(4,7,8). Multimodal IONM approaches are commonly preferred because they allow simultaneous assessment of different neural pathways^(7,8). Somatosensory evoked potentials (SEP) and motor evoked potentials (MEP) provide information regarding the functional integrity of sensory and motor tracts, whereas electromyography (EMG)-based techniques can offer immediate feedback during neural irritation or following direct and indirect nerve stimulation⁽⁹⁻¹²⁾.

In endoscopic lumbar procedures, early detection of intraoperative neural irritation through free-running EMG (freeEMG) may provide immediate electrophysiological

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Received: 15.06.2026 **Accepted:** 05.10.2026 **Publication Date:** 14.10.2026

Cite this article as: Doğan A, Karırmzada G, Evleksiz D. Real-time multimodal neuromonitoring during unilateral biportal endoscopic lumbar surgery: a single-center safety analysis. J Turk Spinal Surg. 2026;37(4):195-201



feedback and allow the surgical team to reassess ongoing manipulation or operative parameters^(7,9,10,13).

Based on these considerations, the present study aimed to describe intraoperative electrophysiological observations obtained with multimodal IONM during lumbar discectomy and decompression with UBE. Particular attention was given to freeEMG activity occurring during electrocautery use and to changes in these recordings following adjustment of the electrocautery settings. The study was designed to characterize these intraoperative observations rather than to assess the clinical effectiveness of IONM.

MATERIALS AND METHODS

Between January 2024 and June 2025, a total of 78 patients who underwent lumbar discectomy or decompression using UBE without fusion or instrumentation at our institutions were retrospectively reviewed. The study was approved by the Hitit University Local Ethics Committee (approval no: 2025-124, date: 03.06.2025). Owing to the retrospective design of the study, the requirement for informed consent was waived by the ethics committee.

Inclusion Criteria

1. Patients with symptomatic lumbar disc herniation or lumbar spinal stenosis requiring lumbar discectomy or decompression using UBE.
2. Single- or two-level lumbar degenerative pathology treated using UBE.
3. Availability of multimodal IONM (freeEMG, MEP, and SEP) throughout the procedure.
4. Complete perioperative clinical, neurological, and IONM records.
5. Availability of postoperative neurological follow-up.

Exclusion Criteria

1. Multilevel pathology requiring treatment at more than two lumbar levels.
2. Spinal deformity requiring corrective surgery.
3. Radiographic instability or spondylolisthesis requiring instrumented fusion.
4. Patients undergoing concomitant fusion or instrumentation.
5. Spinal infection, tumor, trauma, or other non-degenerative spinal pathology.
6. Incomplete clinical or postoperative follow-up data.
7. Inadequate IONM setup or incomplete neuromonitoring documentation.

Surgical Procedure

All patients underwent surgery according to standard unilateral biportal endoscopic surgical techniques. Decompression alone was performed in 22 patients, whereas 56 patients underwent discectomy. Continuous saline irrigation and clear endoscopic visualization were maintained throughout all stages of decompression and/or discectomy. Electrocautery was used

when necessary for hemostasis and for the management of soft tissues adjacent to the decompression area.

Anesthesia and Neuromonitoring

All procedures were performed under general anesthesia. During intubation, propofol and rocuronium were administered for induction and muscle relaxation. Anesthesia maintenance was achieved using remifentanyl and propofol. Except for the neuromuscular blockade administered during intubation, no additional muscle relaxants were used throughout the intraoperative period.

The multimodal IONM protocol consisted of the following components:

- Continuous freeEMG for real-time detection of spontaneous nerve root activity;
 - MEP recorded from representative upper- and lower-extremity muscles, including the abductor pollicis brevis, rectus femoris, extensor hallucis longus, and abductor hallucis, according to the operative level;
 - SEP for continuous assessment of sensory pathway integrity.
- Preoperative and postoperative motor strength was assessed from the neurological examinations documented in the clinical records. Postoperative motor improvement was based on documented improvement in muscle strength during follow-up rather than on an assessment at a predefined postoperative time point. Baseline MEP and SEP recordings were obtained at the beginning of surgery. During the intraoperative period, continuous multimodal IONM was applied, including ongoing freeEMG surveillance with additional SEP and MEP assessments when required. Changes in MEP and SEP recordings were assessed qualitatively during surgery; amplitude and latency changes were not systematically quantified for retrospective analysis. Free-running EMG activity was interpreted in real time by the same neuromonitoring specialist throughout all procedures. Repetitive or sustained EMG discharges occurring in temporal association with surgical manipulation or electrocautery use were recorded as intraoperative freeEMG events. No predefined quantitative thresholds for discharge duration, frequency, amplitude, or number had been prospectively established. In addition, a reliable distinction between neural irritation and electrocautery-related artifact could not be made retrospectively. Therefore, these events were described as freeEMG activity temporally associated with electrocautery use rather than as confirmed nerve root irritation or neural injury. When sustained or repetitive freeEMG activity was observed, the surgical maneuver and electrocautery settings were reassessed before the procedure was continued. Electrocautery was initially used at 35-40 W and was reduced to 15-20 W when such activity occurred during its use. FreeEMG activity was subsequently observed until it returned to baseline. This adjustment represented an intraoperative response to the electrophysiological finding and was not based on a prospectively defined study protocol.

Statistical Analysis

Descriptive statistical methods were used to summarize the study population and intraoperative findings. Continuous variables are presented as mean $\pm$ standard deviation and range, where available, whereas categorical variables are presented as numbers and percentages. Given the retrospective, single-cohort design and the absence of an unmonitored comparison group, the analyses were primarily descriptive. Clinical and operative characteristics were summarized according to the type of surgical procedure and intraoperative electrophysiological findings. No analysis was intended to determine the independent effect of IONM on postoperative neurological outcomes.

RESULTS

Patient Population

A total of 78 patients who underwent surgery with UBE were included in the study. Demographic characteristics such as age and sex, as well as clinical parameters including spinal pathology type, pathological level, and postoperative complications, were retrospectively evaluated from patient records.

Of the patients, 42 were female and 36 were male. The mean age was 57.3 years (range, 35-78 years). Lumbar disc herniation was identified in 56 patients, whereas 22 patients presented with lumbar spinal stenosis. Preoperative motor weakness was present in 18 cases. The demographic and clinical characteristics of the study population are summarized in Table 1.

Intraoperative Findings

Decompression alone was performed in 22 patients, while 56 patients underwent discectomy. Multimodal IONM with freeEMG, MEP, and SEP was used in all cases. Qualitative changes

in MEP and SEP recordings were observed during surgery; however, these changes were not systematically quantified or analyzed across the study population. Figures 1 and 2 show representative examples of MEP and SEP recordings obtained before and after discectomy and are presented for illustrative purposes.

FreeEMG activity temporally associated with electrocautery use was observed in 32 of 78 patients (41.0%) (Figure 3). In these cases, the electrocautery power was reduced intraoperatively, after which the freeEMG activity returned to baseline. No corresponding new postoperative neurological deficit was identified in these patients.

Postoperative Findings

The mean postoperative follow-up period was 17.4 $\pm$ 8.5 months. No new postoperative neurological deficits were observed during follow-up. Among the 18 patients with preoperative motor weakness, improvement in muscle strength was documented in 14 during postoperative follow-up.

Dural injury occurred in three patients (3.85%) and was recognized intraoperatively in all cases. No postoperative cerebrospinal fluid leakage or pseudomeningocele was observed, and none of these patients required reoperation for the dural injury. Postoperative headache occurred in three patients (3.85%) and resolved with conservative management. In addition, one patient with a history of anticoagulant use developed worsening leg pain during the sixth postoperative hour. Subsequent postoperative lumbar magnetic resonance imaging revealed an epidural hematoma (n=1, 1.28%), and the patient subsequently underwent urgent open surgical evacuation. Following the second operation, the patient was discharged without any neurological deficit. Other postoperative complications are summarized in Table 1.

Table 1. Demographic, clinical, and postoperative characteristics of patients undergoing unilateral biportal endoscopic lumbar surgery (n=78)

Variable	Groups	Number of patients, n (%)
Gender	Female	42 (53.85%)
	Male	36 (46.15%)
Pathology	Lumbar disc herniation	56 (71.79%)
	Lumbar spinal stenosis	22 (28.21%)
Surgical level	L2-3	3 (3.85%)
	L3-4	7 (8.97%)
	L4-5	30 (38.46%)
	L5-S1	38 (48.72%)
Postoperative complications	Dural injury	3 (3.85%)
	Epidural hematoma	1 (1.28%)
	Neural injury	0 (0%)
	Recurrence	2 (2.56%)
	Headache	3 (3.85%)
	Visual loss	1 (1.28%)
	Infection	0 (0%)
	Cerebrospinal fluid fistula	0 (0%)

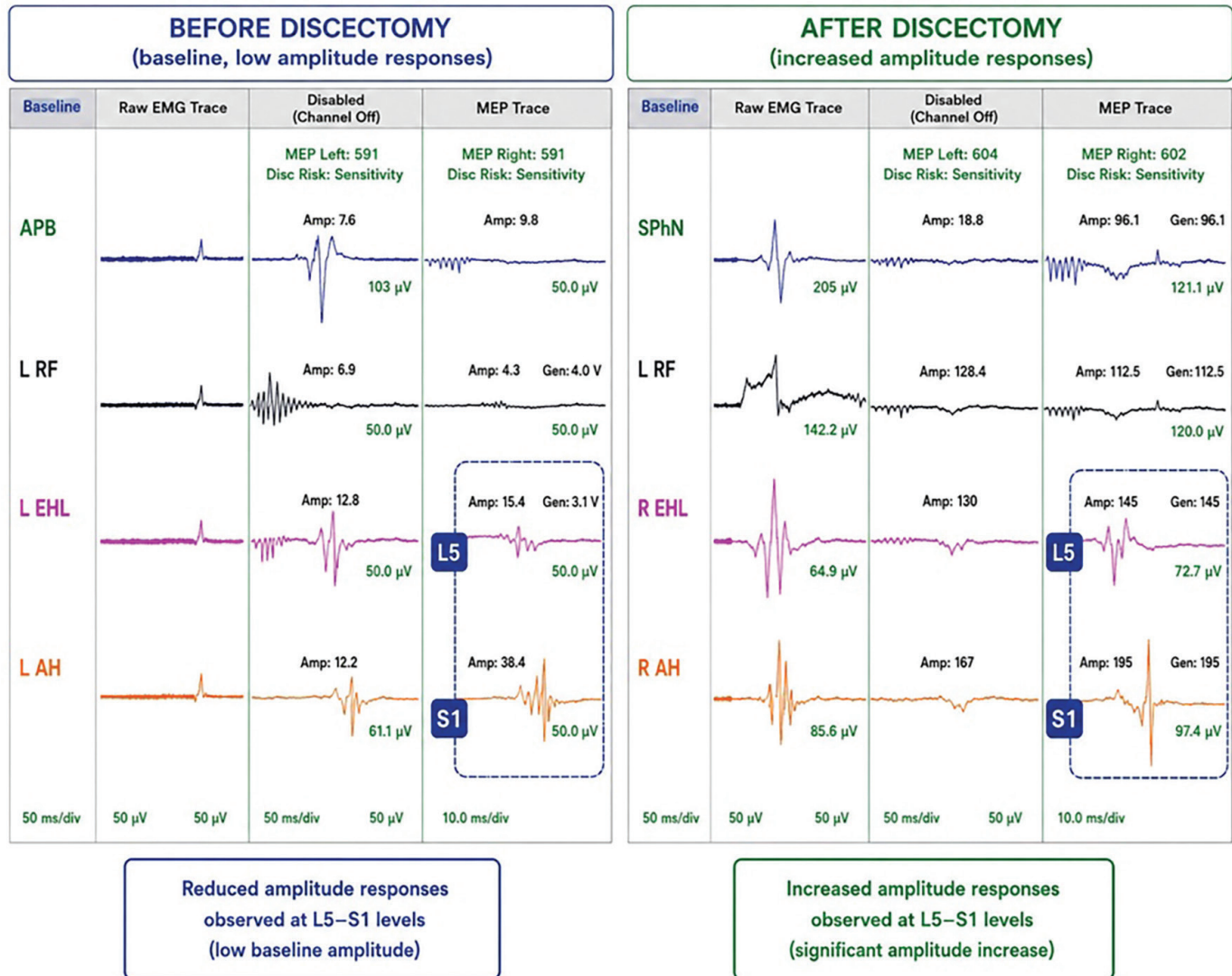


Figure 1. Representative motor evoked potential (MEP) recordings obtained from a patient with L5–S1 lumbar disc herniation before and after discectomy. Baseline recordings demonstrated reduced amplitudes before decompression. Following discectomy, higher MEP amplitudes were observed compared with the baseline recording. EMG: Electromyography, SPhN: Sphincter electromyography channel, APB: Abductor pollicis brevis, RF: Rectus femoris, EHL: Extensor hallucis longus, AH: Abductor hallucis

DISCUSSION

This retrospective study evaluated multimodal IONM, including freeEMG, MEP, and SEP, during lumbar discectomy and decompression using UBE, with a particular focus on intraoperative electrophysiological observations and their relationship to surgical maneuvers. The principal findings of the present study were as follows: (1) freeEMG activity temporally associated with electrocautery use was observed in 41.0% of patients, (2) the freeEMG activity returned to baseline after reduction of the electrocautery power setting, and (3) no new postoperative neurological deficits were identified (0/78). Surgery with UBE requires operative manipulation in close proximity to neural structures, while the limitations of the

endoscopic working corridor and visualization may restrict direct recognition of neural irritation or injury. For this reason, real-time neural monitoring has been considered conceptually valuable during these procedures^(7,9,10,12). Previous studies investigating the use of IONM in surgery with UBE have demonstrated that intraoperative freeEMG changes may provide early warning of neural irritation, allowing timely corrective interventions that may contribute to preservation of neurological function and favorable early postoperative outcomes^(3,5,9,13). Our observations are consistent with the use of freeEMG as an event-related monitoring modality during surgical manipulation. In the present study, freeEMG events were identified qualitatively based on repetitive or sustained electrophysiological activity and its temporal relationship to electrocautery use or the ongoing

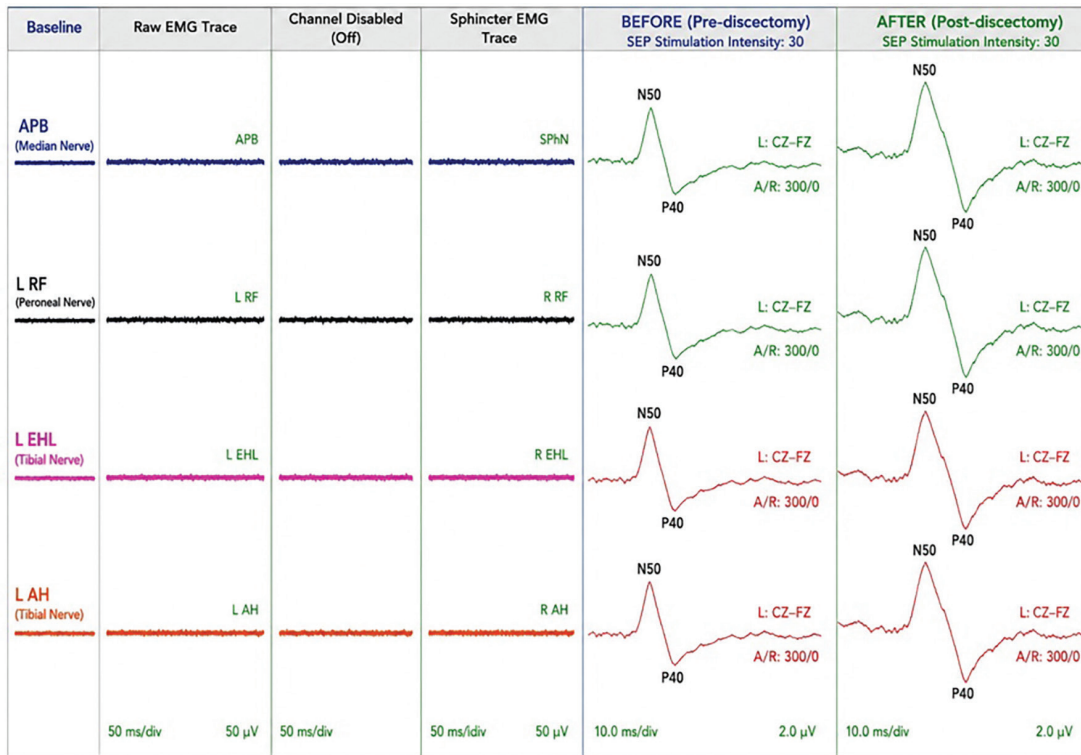


Figure 2. Representative somatosensory evoked potential (SEP) recordings obtained before and after discectomy in a patient with right L5-S1 lumbar disc herniation. Post-discectomy recordings demonstrated higher SEP amplitudes compared with baseline values. EMG: Electromyography, APB: Abductor pollicis brevis, RF: Rectus femoris, EHL: Extensor hallucis longus, AH: Abductor hallucis, CZ-FZ: Central-frontal electrode montage, A/R: Accepted/rejected sweeps

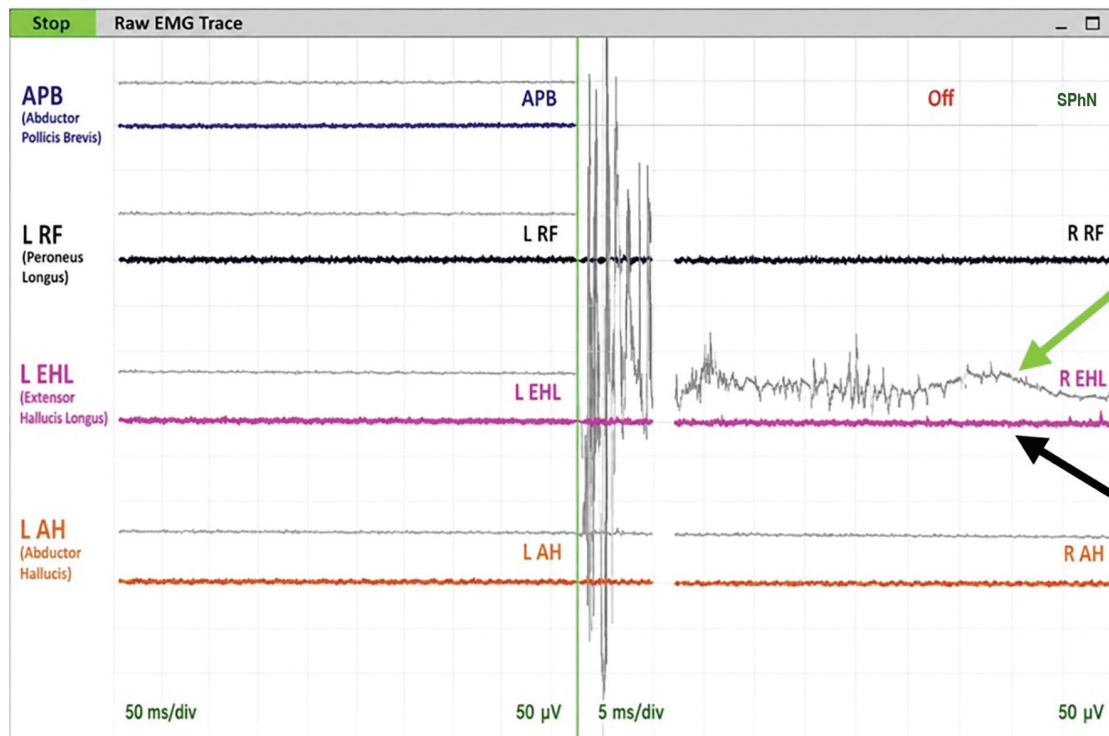


Figure 3. Intraoperative free-running electromyography (freeEMG) recording demonstrating electrophysiological activity observed during electrocautery use (green arrow). Following reduction of the electrocautery setting, the electrophysiological activity returned to baseline (black arrow). APB: Abductor pollicis brevis, RF: Rectus femoris, EHL: Extensor hallucis longus, AH: Abductor hallucis, SPhN: Sphincter electromyography channel

surgical maneuver. These findings prompted intraoperative reassessment and adjustment of the electrocautery settings. Similar observations regarding the use of intraoperative electrophysiological feedback have been reported previously^(9,13-15). However, because the observed activity occurred during electrocautery use, electrocautery-related interference could not be reliably excluded retrospectively. Therefore, the normalization of freeEMG activity after reducing the electrocautery setting cannot be attributed exclusively to resolution of neural irritation. These observations should be interpreted as freeEMG activity temporally associated with electrocautery use rather than evidence of confirmed nerve root injury. Future prospective studies using standardized electrophysiological criteria may help distinguish neurotonic activity from procedure-related artifacts.

Endoscopic spinal surgery is associated with a substantial learning curve, particularly when operating near neural and vascular structures. In surgery with UBE, risk-adjusted learning curve models incorporating neuromonitoring feedback have been proposed to facilitate safer acquisition of technical proficiency by enabling early recognition and correction of potentially hazardous maneuvers through neural irritation alerts^(1,4,16). Although the present study was not specifically designed to evaluate the learning curve, the relatively high frequency of freeEMG activity observed during electrocautery use (41.0%) and the subsequent intraoperative responses illustrate the potential role of real-time electrophysiological feedback during technically demanding endoscopic procedures. Previous learning curve analyses in biportal endoscopic spine surgery have shown that increasing surgical experience affects not only operative duration but also overall procedural safety^(1,16). These observations further support the concept that real-time neural feedback obtained through IONM may provide additional information during surgical technique development and intraoperative decision-making^(7,8).

Several reports in the literature have emphasized the importance of neuromonitoring in endoscopic procedures performed through narrow operative corridors, particularly in anatomically challenging regions where neural structures remain vulnerable during surgical access and decompression^(4,6,13,17). In such procedures, routine monitoring that merely provides retrospective warning signals may be insufficient, whereas immediate intraoperative feedback may have greater clinical relevance^(6,13,15,18). Technical innovations in endoscopic decompression combined with EMG-based neuromonitoring have also been suggested to provide real-time guidance for neural localization and instrument manipulation, potentially reducing the risk of nerve irritation during surgery^(6-8,13).

In studies involving transforaminal endoscopic spine surgery, multimodal neuromonitoring has additionally been reported to assist not only in detecting neural irritation but also in identifying incomplete decompression intraoperatively^(4,6,13). Although the present study focused on the interlaminar approach with UBE,

the fundamental safety rationale remains similar: minimizing delayed or retrospective recognition of neural compromise through proactive intraoperative adjustment and prevention of neural injury.

Study Limitations

No new postoperative neurological deficits were observed in this series; however, in the absence of a control group, this finding cannot be attributed to the use of multimodal IONM. An important limitation of the present study is the absence of validated patient-reported outcome measures, such as the visual analog scale and Oswestry disability index. Consequently, postoperative pain relief, functional recovery, and the overall clinical outcome of the procedure could not be evaluated using standardized outcome measures despite the available follow-up. In addition, because this study was designed as a retrospective descriptive case series, no analytical comparisons were performed between IONM findings and operative or clinical variables. Predefined quantitative electrophysiological alarm thresholds were not prospectively established, which may limit the reproducibility of the IONM findings across different clinical settings. Consequently, the present findings should be interpreted as descriptive observations rather than evidence of clinical effectiveness or prognostic association. Future prospective studies incorporating comparative statistical analyses, standardized outcome measures, and quantitative electrophysiological assessments are needed to further evaluate the clinical value of multimodal IONM. No formal statistical comparison of preoperative and postoperative neurological status was performed because of the limited number of patients with preoperative motor weakness. Another limitation is that quantitative electrophysiological data, including amplitude and latency measurements of MEP and SEP, were not systematically recorded for retrospective analysis. Consequently, the present study was limited to qualitative interpretation of IONM findings, and future prospective studies incorporating standardized quantitative electrophysiological parameters may provide a more objective assessment of intraoperative neural function.

CONCLUSION

In unilateral biportal endoscopic lumbar discectomy and decompression, multimodal IONM using freeEMG, MEP, and SEP provided real-time electrophysiological information throughout the procedure. FreeEMG activity was observed in temporal association with electrocautery use and returned to baseline after modification of the electrocautery settings. However, because this study was retrospective and did not include a control group, these observations cannot establish a protective effect of IONM or its influence on neurological outcomes. Prospective controlled studies are needed to further evaluate its clinical value.

Ethics

Ethics Committee Approval: The study was approved by the Hitit University Local Ethics Committee (approval no: 2025-124, date: 03.06.2025).

Informed Consent: Owing to the retrospective design of the study, the requirement for informed consent was waived by the ethics committee.

Footnotes

Authorship Contributions

Surgical and Medical Practices: A.D., Concept: A.D., D.E., Design: G.K., Data Collection or Processing: A.D., Analysis or Interpretation: G.K., Literature Search: G.K., D.E., Writing: A.D., D.E.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study received no financial support.

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