



Article

Volume-Based Stratification of Lumbar Foraminal Stenosis: A Single-Center Cohort Integrating MRI/CT Morphometrics with Stepwise Interventional, Minimally Invasive and Decompression–Stabilization Surgery

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Abstract

Background: Lumbar foraminal canal stenosis (LFS) is typically multifactorial: disk height loss and bulging, facet hypertrophy/osteophytes, ligamentous thickening, and post-inflammatory or post-interventional scarring. **Methods:** To develop and implement a structured system for surgical care in chronic vertebrogenic pain with radicular features attributable to LFS, integrating population-based MRI morphometrics and interventional therapy response profiling, we conducted a single-center, multi-cohort observational study to develop, operationalize, and internally evaluate a quantitative, volume-integrated diagnostic and treatment stratification framework for LFS. **Results:** A retrospective evaluation of 351 surgically treated patients (2017–2023) was performed to identify structural and clinical drivers of persistent or recurrent pain. Following selective blockades and radiofrequency denervation, radiculopathy regressed in 44.7% of patients, facet-mediated pain improved in 44.0%, and the median pain relief duration was 3–6 months. Oswestry Disability Index (ODI) dynamics after interventional therapy showed significant improvement at 6 months (all $p < 0.001$). Both groups demonstrated significant improvement in VAS, ODI, and SF-36 scores over time. Endoscopic decompression achieved faster early leg pain relief (VAS leg, $p < 0.001$ at 6 and 12 months). ALIF resulted in superior long-term back pain control (VAS back, $p < 0.001$ at 12 and 24 months). At 24 months, pain levels were clinically equivalent between groups, indicating that procedure selection influences pain profile rather than absolute outcome. **Conclusions:** By integrating quantitative foraminal volume, nerve occupancy, and segmental stability, we demonstrated that treatment success in LFS is not determined by the magnitude of decompression alone, but by the precision of phenotypic matching. Indirect decompression, endoscopic foraminotomy, microsurgical decompression, and fusion-based stabilization each have a rational role when aligned with the biomechanical context rather than applied reflexively.

Keywords: lumbar foraminal stenosis; morphometrics; MISS; surgical decompression; neurosurgery; radicular pain; grading system



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1. Introduction

Low back pain (LBP) remains the leading global cause of disability and a major driver of healthcare utilization. In 2020, LBP affected around 619 million people worldwide, with projections rising by mid-century, largely due to aging and population growth [1,2]. Although many cases are nonspecific, a clinically important subset is generated by structural degenerative pathology producing segmental mechanical pain and/or radicular syndromes. Lumbar foraminal stenosis (LFS) is a frequent but under-recognized generator of chronic monoradicular pain, often presented without the dramatic central canal compromise that triggers rapid surgical decision-making. LFS is typically multifactorial: disk height loss and bulging, facet hypertrophy/osteophytes, ligamentous thickening, and post-inflammatory or post-interventional scarring may converge to reduce perineural fat and distort the exiting nerve root trajectory. This “hidden” compressive phenotype contributes to diagnostic uncertainty and to apparent “failed treatment,” especially when symptoms persist despite technically adequate central decompression or when instability evolves after repeated decompressive procedures.

A critical barrier in LFS care is the absence of a unified quantitative framework linking imaging severity to symptom burden, stability status, and the selection of interventional vs. minimally invasive decompression vs. decompression–stabilization strategies. Existing MRI grading approaches provide reliable visual categorization of foraminal stenosis—most notably the Lee MRI grading system (grades 0–3) based on perineural fat obliteration and nerve root morphologic change [3]. In parallel, central canal morphology is frequently staged using qualitative systems such as Schizas grades, which help stratify central stenosis but do not resolve the frequent scenario of severe radiculopathy with only mild-to-moderate central canal compromise [4]. Degenerative substrate characterization commonly relies on standardized imaging scales, including Pfirrmann disk degeneration grading and Fujiwara facet degeneration grading, which inform the likely pain generator and mechanical contribution to stenosis [5,6]. Finally, spinal motion segment instability is a decisive modifier of surgical choice; practical clinical checklists derived from Panjabi’s instability constructs are widely used to operationalize “stable vs. unstable” degenerative phenotypes [7–11].

Within this context, we designed a volume-based morphometric method for the lumbar foraminal canal, intended as an adjunct to visual grading. The premise is straightforward: foraminal stenosis is not only a “shape” problem but also a space-occupancy problem, in which the clinically relevant question is whether the available foraminal space is sufficient for the exiting nerve root under physiologic loading and motion. A volumetric parameter, derived from reproducible MRI/CT measurements, may strengthen decision-making in controversial cases, improve alignment between symptoms and imaging, and support algorithmic selection of staged care.

Existing assessments of LFS have largely relied on qualitative MRI grading systems, linear morphometric measurements, or area-based parameters. Qualitative systems such as the Lee classification are practical and clinically familiar, but they primarily describe perineural fat obliteration and nerve root deformation rather than quantifying the total available spatial capacity of the foramen. Linear parameters such as foraminal height and width are easy to reproduce but may oversimplify a three-dimensional anatomical corridor with irregular osseous and soft-tissue boundaries. Cross-sectional area measurements provide additional spatial information, but they remain plane-dependent and do not directly describe the relationship between the exiting nerve root and the available foraminal canal. These limitations are particularly relevant in borderline stenosis, multilevel degeneration, disk height collapse, and cases where symptoms appear disproportionate to qualitative imaging grade.

The volumetric approach proposed in this study was developed to complement conventional grading by estimating foraminal capacity and nerve–foramen spatial competition. Foraminal volume represents the available canal space, whereas nerve occupancy expresses the proportion of that space occupied by the exiting root. This distinction may be clinically relevant because two foramina with similar qualitative grades may differ substantially in residual spatial reserve, especially across lumbar levels and in the presence of disk collapse, facet hypertrophy, or osteophyte formation.

Explicit Hypothesis and Objectives for the End of the Introduction

We hypothesized that a combined framework integrating Lee grade, static foraminal volume, nerve occupancy, and segmental stability would provide more granular treatment stratification in LFS than qualitative imaging assessment alone. We further hypothesized that lower foraminal volume and higher nerve occupancy would be associated with clinically relevant radicular symptoms, reduced durability of interventional treatment, and the need for surgical escalation. The objectives were (1) to operationalize a reproducible MRI/CT-based method for estimating foraminal volume and nerve occupancy; (2) to establish asymptomatic morphometric reference values across lumbar levels; (3) to characterize the response and durability of interventional therapy in patients without dominant central canal stenosis; (4) to evaluate clinical and morphometric outcomes after algorithm-guided surgical treatment; and (5) to internally assess whether combining Lee grade, foraminal volume, nerve occupancy, and stability status can support treatment stratification in LFS.

A combined framework integrating Lee grade + foraminal canal volume + stability status improves selection of the appropriate treatment tier (interventional vs. decompression vs. decompression–stabilization) and is associated with meaningful improvements in patient-reported outcomes. The purpose of this paper is to develop and implement a structured system for surgical care in chronic vertebrogenic pain with radicular features attributable to LFS, integrating (1) population-based MRI morphometrics, (2) interventional therapy response profiling, and (3) comparative outcomes of minimally invasive decompression and decompression–stabilization approaches.

2. Materials and Methods

2.1. Study Design, Objectives, and Reporting Framework

We conducted a single-center, multi-cohort observational study to develop, operationalize, and internally evaluate a quantitative, volume-integrated diagnostic and treatment stratification framework for LFS. The program was prespecified as four complementary cohorts designed to (1) define structural drivers of postoperative dissatisfaction and revision, (2) establish normative foraminal volumetric anatomy in asymptomatic adults, (3) quantify the magnitude and durability of interventional pain procedures in chronic vertebrogenic pain without dominant central canal stenosis, and (4) assess clinical and morphometric outcomes after algorithm-guided surgical management across procedure classes. The manuscript is reported in accordance with STROBE guidance for cohort studies; algorithm transparency (predictors, thresholds, and endpoints) was prespecified prior to comparative analyses to minimize post hoc optimization.

2.2. Setting and Data Sources

All cohorts were derived from the Neurosurgery Department, National Clinical Center No. 2, Federal State Budgetary Scientific Institution “Russian Scientific Center of Surgery named after Academician B.V. Petrovsky” (Moscow, Russia). Data were obtained from institutional electronic medical records, radiology PACS archives (MRI/CT DICOM datasets),

operative reports, interventional pain procedure logs, and standardized patient-reported outcome measures (PROMs) collected during routine follow-up.

2.2.1. Case Identification, Sampling Strategy, and Interventional Durability Analysis

Cohort A: Historical Surgical Cohort

Eligible cases were identified through a structured query of the institutional surgical registry and operative logbooks. All lumbar spine procedures performed for degenerative pathology during the study interval were screened using procedural codes and operative report keywords corresponding to decompression and/or fusion techniques (microdiscectomy, decompressive laminectomy/laminotomy, endoscopic decompression, TLIF/PLIF, ALIF, interspinous stabilization). Consecutive sampling was applied: all eligible operations meeting the inclusion criteria during the defined time frame were included without outcome-based selection.

Exclusion criteria were applied sequentially: (1) non-degenerative etiology (tumor, infection, trauma, inflammatory disease); (2) primary deformity correction as the principal indication; and (3) incomplete operative or imaging documentation preventing revision adjudication. For revision cases, the dominant structural cause of recurrence was determined through imaging review and operative confirmation using a standardized adjudication form.

Cohort B: Asymptomatic MRI Morphometric Reference Cohort

Lumbar MRI examinations were identified retrospectively from the institutional PACS database using a date-restricted query. Consecutive scans performed for non-radicular indications or incidental findings were screened. Electronic records were reviewed to confirm: (1) no prior lumbar spine surgery and (2) no documented lumbar radicular syndrome requiring medical evaluation within the preceding 12 months.

Sequential exclusions were applied: prior lumbar surgery; documented radiculopathy within 12 months; non-degenerative pathology on imaging; severe central canal stenosis (Schizas C/D); and inadequate imaging quality for volumetric analysis (poor boundary visualization, non-diagnostic axial series). Degenerative findings were permitted unless they precluded reliable morphometric measurement. Sampling proceeded consecutively by imaging date until the target sample size was achieved.

Cohort C: Interventional Therapy Cohort

Patients were identified from the institutional interventional procedure registry and fluoroscopy suite logs using procedural filters for lumbar selective nerve root blocks, medial branch blocks, sacroiliac joint blocks, and radiofrequency denervation.

All patients undergoing their first qualifying interventional episode during the study interval were included consecutively.

Eligibility required: (1) chronic vertebrogenic pain and/or radiculopathy refractory to conservative care; (2) schizas A/B central canal morphology; and (3) imaging concordant with degenerative pathology.

Exclusion criteria: (1) severe or progressive neurological deficit requiring urgent surgery; (2) non-degenerative etiology; and (3) incomplete documentation preventing phenotype classification or response assessment. The index date was defined as the first intervention in the staged diagnostic–therapeutic sequence.

Cohort D: Algorithm-Guided Surgical LFS Cohort

Surgical candidates were identified through the spine surgery scheduling system and operative registry using diagnostic and procedural filters corresponding to foraminal stenosis and foraminal decompression/fusion procedures. Consecutive sampling was

applied. All patients meeting prespecified eligibility criteria and treated surgically under the algorithm were included.

Eligibility required: Age ≥ 18 years, Monoradicular syndrome with level/side concordance, MRI-confirmed foraminal stenosis (Lee grade 1–3) [1], and failure of structured nonoperative management ≥ 12 weeks.

Sequential exclusions were applied, including dominant central stenosis (Schizas C/D); primary deformity indication (coronal Cobb angle $> 10^\circ$ requiring deformity correction); non-degenerative etiology; imaging–symptom mismatch; inadequate imaging for volumetric assessment; and missing baseline PROM data. Prior surgery at the index level was permitted only if morphometric boundaries remained measurable and pathology was predominantly foraminal.

2.3. Ethics, Consent, and Confidentiality

The study protocol was approved by the Institutional Review Board of National Clinical Center No. 2, B.V. Petrovsky Russian Scientific Center of Surgery, Moscow, Russian Federation (IRB/LEC-1417/2026). The retrospective components used de-identified data; the prospective follow-up PROM collection was performed under written informed consent, where required by local regulation. All analyses were conducted on anonymized datasets with restricted access.

2.4. Cohort Architecture and Independence

The four cohorts were constructed to answer complementary questions within the same institutional research program. To preserve analytic independence, subjects in the asymptomatic reference cohort were not included in symptomatic cohorts. Patients who underwent interventional therapy and later progressed to surgery were only analyzed in the interventional cohort until the date of surgical escalation. Their subsequent surgical episode was counted once in the algorithm-guided surgical cohort. No patient contributed duplicate postoperative outcome records for the same index surgical episode. This rule was applied before statistical analysis to avoid double-counting of outcomes. The total program dataset comprised $n = 1570$ individuals, partitioned into four components:

- A. Historical surgical cohort (2017–2018; $n = 351$): Used to describe primary procedure distribution, revision incidence, and structural causes of persistent/recurrent symptoms.
- B. Asymptomatic morphometric MRI reference cohort (2017–2023; $n = 500$): Used to establish level- and side-specific normative foraminal canal morphometrics and nerve–foramen spatial relationships.
- C. Interventional therapy cohort (2017–2023; $n = 463$): Patients with chronic vertebrogenic pain and/or radiculopathy without dominant central canal stenosis beyond Schizas A/B, treated with staged diagnostic blocks and interventions to quantify response magnitude, durability, and escalation to surgery.
- D. Algorithm-guided surgical LFS cohort (2017–2023; $n = 256$): Comparative cohort of surgically treated LFS patients selected and managed using the prespecified volume- and stability-guided algorithm, with standardized morphometric and PROM follow-up.

Among the 463 patients included in the interventional therapy cohort, 142 patients eventually met criteria for surgical escalation and were subsequently included in the algorithm-guided surgical LFS cohort. These patients were only analyzed in Cohort C up to the date of surgery, after which their surgical episode was counted once in Cohort D. This censoring strategy was prespecified to avoid double-counting of postoperative outcomes. The crossover subgroup may represent a more treatment-resistant phenotype, characterized by recurrent pain after initially successful interventions, persistent concordant radiculopathy, or progressive mechanical foraminal compromise. Therefore, selection bias related to

escalation should be considered when interpreting the surgical cohort, as patients crossing from Cohort C to Cohort D were not equivalent to patients who achieved durable benefit from interventional therapy.

Symptomatic cohorts (C and D) were only allowed to overlap if the patient underwent interventional therapy first and later met surgical criteria; in that scenario, the surgical episode was only counted once in cohort D, and interventional outcomes were analyzed up to the date of surgery (censoring for escalation).

2.5. Eligibility Criteria

2.5.1. Algorithm-Guided Surgical Cohort (Primary Evaluative Cohort; $n = 256$)

Inclusion criteria are (a) age ≥ 18 years; (b) unilateral or predominant radicular syndrome consistent with a single exiting root distribution (dermatomal sensory symptoms and/or concordant motor/reflex changes); (c) imaging-confirmed LFS at a concordant level/side on MRI with or without CT confirmation; (d) foraminal stenosis graded Lee 1–3; (e) disk degeneration Pfirrmann II–V and facet degeneration Fujiwara I–IV recorded for phenotype description; and (f) failure of structured nonoperative care ≥ 12 weeks, including, at minimum, activity modification, analgesics/anti-inflammatories if tolerated, physiotherapy-guided core stabilization, and/or targeted injections when indicated.

Exclusion criteria are (a) imaging–symptom nonconcordance (level/side mismatch between symptoms and imaging); (b) dominant central canal stenosis phenotype: Schizas C/D; (c) primary deformity indication: coronal Cobb angle $> 10^\circ$ requiring deformity correction as the primary strategy; (d) non-degenerative etiologies (infection, tumor, inflammatory spondyloarthropathy, congenital anomalies); and (e) prior surgery at the index level was permitted only if sufficient imaging was available for reliable morphometrics and the compressive substrate was predominantly foraminal/extraforaminal.

2.5.2. Asymptomatic Reference Cohort ($n = 500$)

Inclusion required the absence of low back pain with radicular features requiring medical evaluation within the preceding 12 months and no prior lumbar spine surgery. Subjects with incidental mild degenerative changes were not excluded to preserve real-world normative variability, but any level meeting Lee ≥ 2 with clinical symptoms was excluded by design.

2.5.3. Interventional Cohort ($n = 463$)

Adults with chronic low back pain and/or radiculopathy refractory to conservative therapy and Schizas A/B central canal morphology were included. Patients with severe motor deficits requiring urgent decompression or with non-degenerative etiologies were excluded.

2.6. Clinical Assessment and Outcome Measures

All symptomatic patients underwent standardized assessment, including (1) neurological examination (MRC motor grading, dermatomal sensory mapping, deep tendon reflexes); (2) provocation tests (e.g., straight leg raise/femoral stretch where clinically applicable); and (3) pain phenotype classification integrating clinical findings and response to targeted diagnostic blocks (radicular vs. discogenic vs. facet-mediated vs. sacroiliac joint-mediated vs. myofascial).

Primary endpoints (algorithm-guided surgical cohort): change in disability at 12 months measured by Oswestry Disability Index (ODI). Secondary endpoints (algorithm-guided surgical cohort): VAS leg pain and VAS back pain changes at 6 and 12 months; SF-36 physical (PF/PH) and mental (MH) domain changes at 12 months; patient global success at 12 months using MacNab categories; morphometric change (foraminal canal

volume and occupancy metrics) from preoperative to early postoperative imaging (time window specified below). Safety endpoints: perioperative complications, readmissions, reoperations (definitions below).

2.7. Imaging Acquisition, Grading, and Standardization

A lumbar MRI was performed using institutional standard high-resolution protocols. For reproducibility, measurement was performed on a) sagittal T2-weighted series for level identification and disk height context, and b) axial T2-weighted series aligned to each disk level (or oblique-axial reformats when available) for foraminal assessment. Slice thickness and in-plane resolution were recorded for each scan, and only studies with adequate visualization of the foraminal boundaries and exiting root were included in volumetric analyses. CT protocol was used to refine osseous contributors (facet hypertrophy/osteophytes, endplate irregularity) and to assist in cases with limited MRI boundary visualization. CT measurements were not substituted for MRI volumetry unless the segmentation plane could be matched.

Qualitative grading systems:

- Foraminal stenosis: Lee classification [1] MRI grade 0–3.
- Central canal morphology: Schizas grade (A/B eligible for cohorts C and D; C/D excluded from D).
- Disk degeneration: Pfirrmann.
- Facet degeneration: Fujiwara.

All grades were recorded per index level and adjacent levels (one above/one below) to support phenotype and confounding assessment.

2.8. Foraminal Volumetry: Measurement Workflow

Measurements were performed using RadiAnt DICOM Viewer (2020.2). Two independent readers (a neuroradiologist and a spine neurosurgeon) underwent joint calibration on a training set (≥ 30 randomly selected foramina) to harmonize landmark selection. Readers were blinded to clinical outcomes and surgical group assignment at the time of measurement. Discrepancies exceeding a prespecified tolerance (see below) were adjudicated by consensus.

To standardize across patients and levels, the foraminal canal region was defined by reproducible osseous ligamentous boundaries:

- Superior–inferior boundaries: inferior border of the pedicle above and superior border of the pedicle below.
- Anterior boundary: posterolateral vertebral body/disk/osteophyte complex.
- Posterior boundary: superior articular process/facet complex and ligamentous elements visible on MRI.

Measurements were performed using RadiAnt DICOM Viewer 2020.2. Assessments were conducted independently by an experienced radiologist and neurosurgeon, blinded to clinical data to avoid bias.

Based on the data obtained in the course of a retrospective study, an algorithm for diagnosing patients with the clinical picture of chronic vertebrogenic pain in combination with monoradicular pain syndrome caused by foraminal canal stenosis was developed, based on a combination of the Lee classification [1] and indicators for calculating the volume of the foraminal canal (proposed by the author) based on the results of an MRI examination. The stages of surgical care for this category of patients have been developed (Figure 1).

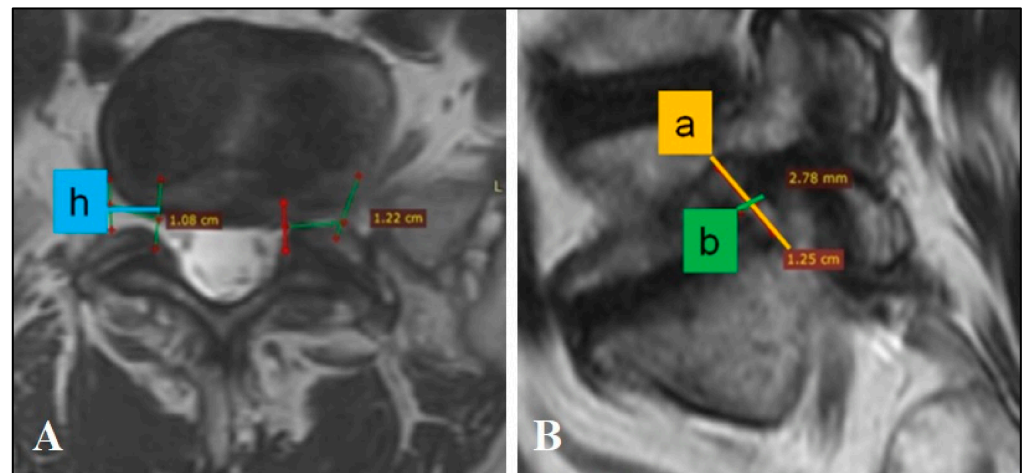


Figure 1. It shows axial (A) and sagittal (B) views of the lumbar spine with measurements. h, osseous depth of the foraminal canal; a, major orthogonal diameter of the spinal canal; b, minor orthogonal diameter of the spinal canal.

For the diagnosis of foraminal stenosis, the classification of Lee et al. (2010) [1] was used (Figure 2):

- Grade 0 (normal) is where fat surrounds the nerve root circumferentially.
- Grade 1 is a mild degree of stenosis characterized by obliteration of the perineural tissue surrounding the nerve root transversely or vertically.
- Grade 2 means a moderate degree in which there is a marked narrowing of the foramen in width and height, although without morphological changes in the nerve root.
- Grade 3 is characterized either by the destruction of the nerve root or by morphological changes.

2.8.1. Plane Selection and Measurement Points

For each index level and side (L1–L2 through L5–S1), measurements were obtained at a standardized “mid-foraminal” plane:

1. Identify the disk level on sagittal T2.
2. Select the axial slice (or oblique-axial reformat) passing through the maximum visualization of the exiting nerve root within the foramen.
3. Confirm that the slice lies between pedicles (to avoid the far-lateral extraforaminal region).

2.8.2. Elliptical-Cylinder Volume Model

The foraminal canal cross-section at the selected plane was approximated as an ellipse with maximal long-axis diameter of the foramen (a) and maximal short-axis diameter orthogonal to a (b). The foraminal depth parameter, h, was defined on the standardized mid-foraminal axial or oblique-axial plane using fixed osseous landmarks. To improve reproducibility, h was measured along the expected course of the exiting nerve root using the following references:

- Medial landmark: medial pedicle border at the transition between the lateral recess and the entrance of the neural foramen.
- Anterior reference: posterior vertebral body / disco-osteophyte line at the index level.
- Posterior reference: anterior surface of the superior articular process / facet complex.
- Lateral landmark: lateral cortical margin of the pedicle or the point where the exiting root leaves the osseous foraminal corridor.

- Measurement axis: medial-to-lateral foraminal depth along the expected trajectory of the exiting nerve root, avoiding far-lateral extraforaminal tissue.

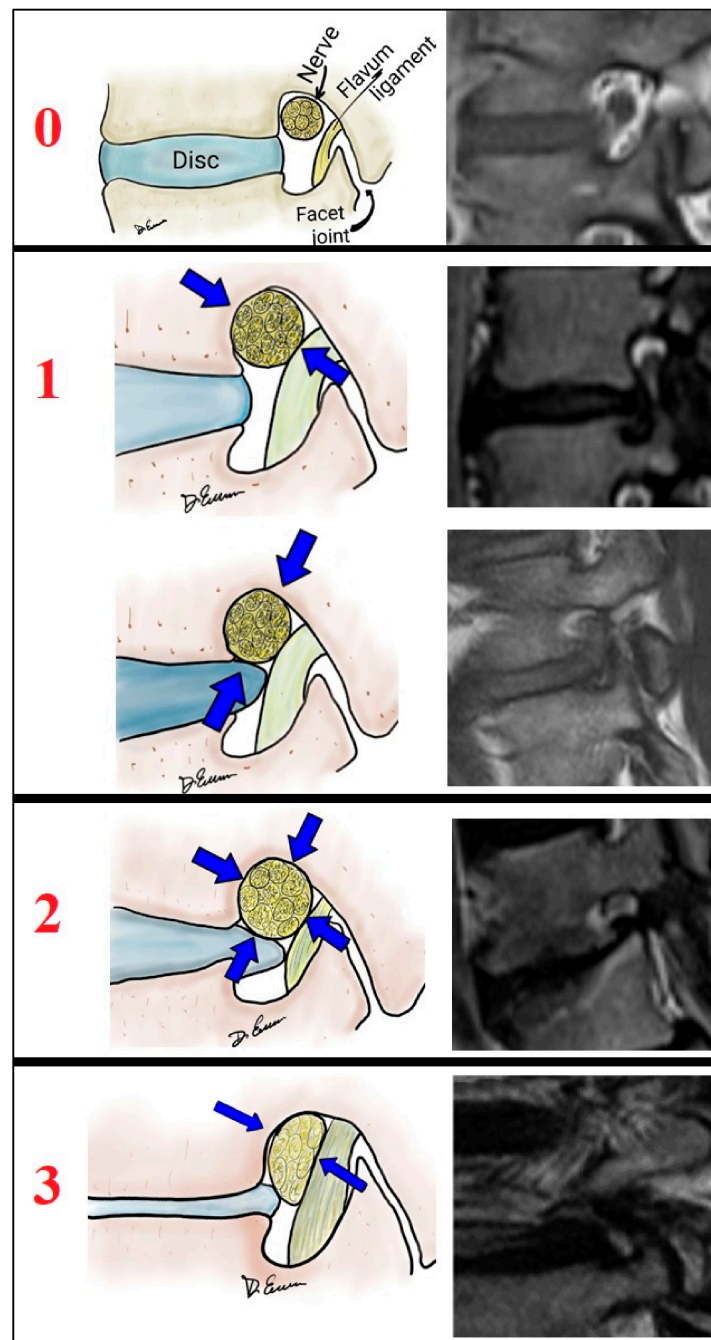


Figure 2. It shows the foraminal stenosis grade according to the classification of Lee et al. In grade 0, fat surrounds the nerve root circumferentially. In grade 1, anteroposterior narrowing due to thickening/protrusion of the yellow ligament or upper inferior narrowing due to disk and/or osteophyte overgrowth or loss of disk height was reported. In grade 2, marked narrowing of the foramen in width and height, although without morphological changes in the nerve root, was observed. In grade 3, multidirectional impairment due to degenerative facet joint hypertrophy, thickening/bulging of the ligament flavum, disk and/or osteophyte disorder, and/or loss of disk height was reported.

Thus, h represented the reproducible osseous depth of the foraminal canal rather than an arbitrary anteroposterior distance. The same landmark definition was applied for preoperative and postoperative measurements.

Foraminal canal volume was computed as:

$$V_{\text{foramen}} = (\pi \cdot a \cdot b \cdot h)/4$$

with all dimensions in millimeters and volume reported in mm³.

2.8.3. Nerve–Foramen Spatial Relationship (Occupancy)

A nerve occupancy metric was computed to express space competition:

- The exiting nerve root was measured at the same plane using two orthogonal diameters (a_n , b_n) to approximate nerve cross-sectional area as an ellipse.
- Nerve “segment length” (h) was set equal to the measured foraminal h to maintain geometric compatibility.

Nerve volume proxy:

$$V_{\text{nerve}} = (\pi \cdot a_n \cdot b_n \cdot h)/4$$

Occupancy (%):

$$\text{Occupancy} = (V_{\text{nerve}}/V_{\text{foramen}}) \times 100$$

This occupancy metric was used for: (i) normative reference mapping; (ii) severity stratification among symptomatic levels; and (iii) quantifying decompression effect.

2.8.4. Measurement Quality Control and Reproducibility

Interobserver agreement for a , b , h , V_{foramen} , and occupancy was assessed using a two-way random effects intraclass correlation coefficient (ICC) [1,2] with 95% confidence intervals.

A priori discrepancy rule: if the absolute difference between readers exceeded 10% for V_{foramen} or occupancy, the measurement was repeated and adjudicated. Intraobserver repeatability was tested in a random subset ($\geq 10\%$ of measurements) with a minimum 2-week washout.

2.9. Stability Assessment

2.9.1. Radiographic Assessment

Instability was assessed as a treatment-effect modifier and was a determinant of whether decompression alone or decompression–stabilization was indicated.

All surgical candidates underwent (a) standing AP/lateral radiographs; (b) flexion–extension lateral radiographs when clinically safe and not contraindicated; and (c) MRI assessment for facet effusion, disk collapse, and alignment.

2.9.2. Instability Criteria (Reproducible Thresholds)

A segment was classified as “unstable” if any of the following were present at the index level: (a) dynamic translation ≥ 3 mm on flexion–extension; (b) dynamic angular motion $\geq 10^\circ$ at L1–L5 or $\geq 15^\circ$ at L5–S1, or clear hypermobility relative to adjacent levels; (c) Meyerding degenerative spondylolisthesis $\geq$ Grade I with concordant symptoms and imaging; (d) planned decompression requiring $>50\%$ facetectomy (iatrogenic destabilization risk); and (e) recurrent foraminal stenosis with radiographic signs of progressive collapse/instability after prior decompression. These criteria were recorded in a structured form and applied before the final surgical assignment.

2.10. Interventional Therapy Protocol (Cohort C)

Patients underwent staged diagnostic and therapeutic interventions to identify dominant pain generators and define response durability. Diagnostic blocks (performed as indicated): (a) selective nerve root (transforaminal) blocks; (b) medial branch blocks for suspected facet pain; and (c) sacroiliac joint blocks for SIJ pain suspicion. A block was

considered “positive” if it produced $\geq 50\%$ short-term pain reduction with functional improvement during the expected anesthetic window.

Medial branch radiofrequency ablation was performed under fluoroscopy:

- Cannula length 100–150 mm; active tip 5–10 mm.
- Lesioning temperature 80 °C for 90 s.
- Levels treated were selected according to positive diagnostic blocks.

Interventional outcomes were recorded at 6 weeks and 6 months. For patients later escalated to surgery, interventional outcomes were censored at the surgical date.

2.11. Surgical Techniques and Group Definitions (Cohort D)

All operations were performed by experienced spine surgeons using standardized institutional pathways (antibiotics, DVT prophylaxis, mobilization).

2.11.1. Group 1: Minimally Invasive/Indirect Decompression ($n = 119$)

Endoscopic foraminal decompression (EN; $n = 80$).

Indicated for stable segments with disk-related foraminal/extraforaminal compression and limited facet hypertrophy. Standard technique included targeted foraminotomy with preservation of stabilizing elements where feasible.

ALIF/arthroplasty indirect decompression ($n = 39$).

Indicated when disk height loss and sagittal mechanics contributed to foraminal narrowing with preserved or mild facet degeneration and without criteria mandating posterior decompression. Cage placement and/or arthroplasty aimed to restore disk height and foraminal dimensions; supplemental posterior fixation was used when needed per stability criteria.

2.11.2. Group 2: Direct Decompression vs. Decompression–Stabilization ($n = 137$)

Microsurgical foraminal decompression (MX; $n = 65$).

Indicated for stable stenosis dominated by facet hypertrophy/osteophytes. Partial facetectomy was limited to $\leq 50\%$ to preserve stability.

TLIF decompression–stabilization ($n = 72$).

Indicated for unstable segments, advanced degeneration, synovial cyst/combined stenosis requiring extensive decompression, or when destabilizing decompression was anticipated. Standard TLIF included decompression, interbody fusion, and pedicle screw fixation.

2.12. Follow-Up Schedule, Imaging Timing, and Safety Endpoints

PROMs were collected at baseline and at 6 months, 12 months, and 24 months post-procedure. A 6-week visit was used for early safety and symptom trajectory documentation. Postoperative imaging for morphometric “volume gain” analysis was performed in a standardized early window (e.g., 6 weeks to 3 months; exact window recorded per patient) to minimize confounding from late remodeling.

Complications were categorized as intraoperative, early postoperative (≤ 30 days), and late (>30 days). Reoperation was defined as any return to the operating room at the index level. Adjacent segment disease was defined as new symptomatic adjacent pathology supported by imaging and requiring intervention.

2.13. Statistical Analysis Plan

Analyses were performed using StatTech v4.8.8. Continuous variables were summarized as mean $\pm$ SD or median (Q1–Q3) based on distribution, and categorical variables as counts and percentages.

Between-group comparisons used:

- Kruskal–Wallis with Dunn post hoc and Holm correction (≥ 3 groups).
- Mann–Whitney U (2 groups).
- χ^2 or Fisher exact (categorical).

Within-patient longitudinal comparisons used:

- Wilcoxon signed-rank (paired).
- Friedman with Conover–Iman post hoc and Holm correction (≥ 3 time points).

Association modeling (prespecified):

- Multivariable linear regression for continuous outcomes (ODI, VAS, SF-36 changes).
- Multivariable logistic regression for binary outcomes (MacNab success; reoperation).
- Covariates included age, sex, index level, Pfirrmann grade, Fujiwara grade, baseline PROMs, Lee grade [1], foraminal volume/occupancy, and instability status. Model diagnostics included assessment of collinearity and goodness-of-fit.

Effect sizes are reported as β coefficients or odds ratios (OR) with 95% confidence intervals. Significance threshold was $p < 0.05$ (two-sided).

2.14. Missing Data Handling

PROM missingness was evaluated at each follow-up time point. Missing PROM data were 3.9% at 6 months, 7.8% at 12 months, and 12.5% at 24 months. Because missingness was below 10% at 6 and 12 months, complete-case analysis was used for the primary 12-month endpoint and early secondary endpoints. At 24 months, missingness exceeded the prespecified 10% threshold; therefore, multiple imputation with chained equations was performed for sensitivity analysis of 24-month PROM outcomes. The imputation model included age, sex, baseline PROMs, index level, Lee grade, foraminal volume, nerve occupancy, instability status, and procedure group. Results from imputed analyses were compared with complete-case analyses to assess robustness.

3. Results

3.1. Retrospective Analysis of Surgical Outcomes and Causes of Treatment Dissatisfaction

A retrospective evaluation of 351 surgically treated patients (2017–2023) was performed to identify structural and clinical drivers of persistent or recurrent pain. The median patient age was 57 years, with no clinically relevant sex-related differences (men 58.1%, women 41.9%).

The distribution of primary surgical procedures is summarized in Figure 3A. Decompressive procedures without stabilization predominated (64.9%), whereas decompressive-stabilizing procedures accounted for 35.1% of operations.

Revision surgery was required in 70 patients (19.8%), most commonly within the first 24 months after the index procedure. The leading causes of recurrent symptoms are shown in Figure 3B, with foraminal stenosis-related pathology representing the dominant structural substrate:

- Foraminal canal stenosis: 8.26%.
- Recurrent foraminal stenosis: 3.9%.
- Adjacent segment disease: 3.7%.
- Fixation instability: 2.1%.
- Pseudoarthrosis: 1.13%.

Notably, 78.6% of patients undergoing revision surgery experienced clinically meaningful improvement in disability (ODI), while 21.4% had persistent pain without central canal stenosis (Schizas C/D), highlighting the diagnostic complexity of isolated foraminal pathology.

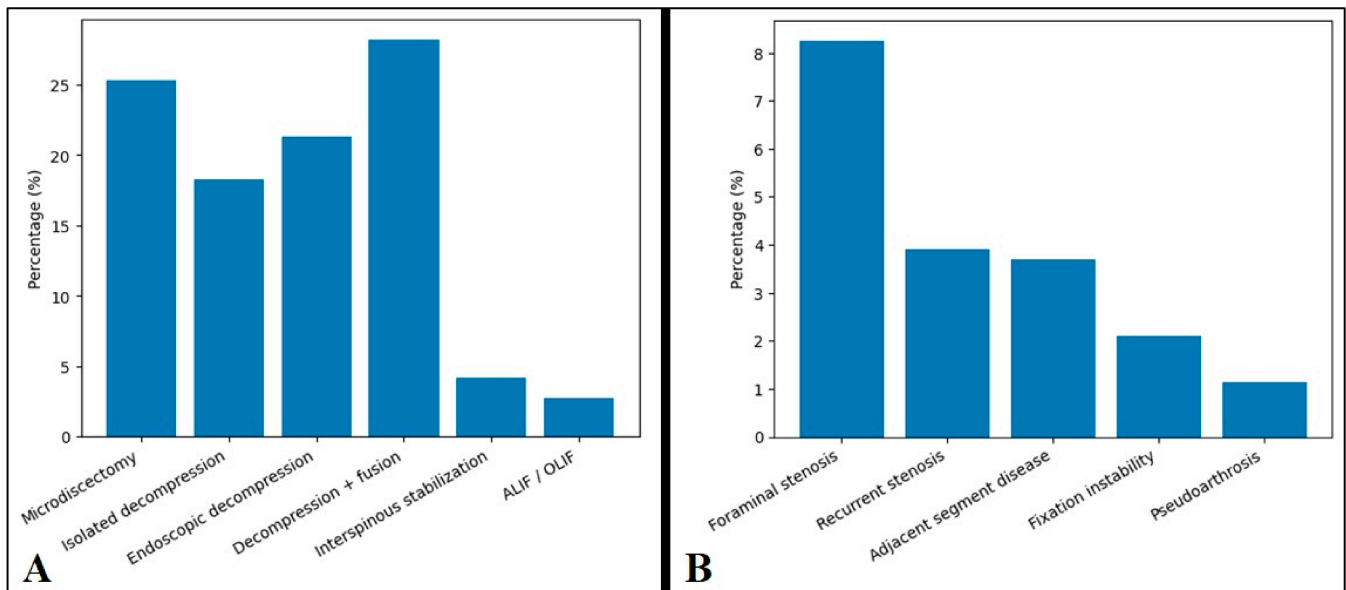


Figure 3. (A) Distribution of primary lumbar surgical procedures in the retrospective cohort. Decompressive procedures without fusion predominated, including microdiscectomy (25.3%), isolated spinal canal decompression (18.3%), and endoscopic decompression (21.3%). Decompression combined with fusion accounted for 28.2% of cases, while interspinous stabilization (4.2%) and anterior approaches (ALIF/OLIF, 2.7%) were less frequently applied. (B) Etiology of persistent or recurrent pain after lumbar spine surgery. Analysis of revision cases demonstrated that foraminal canal pathology represents the most frequent structural cause of postoperative pain recurrence. Foraminal stenosis and recurrent foraminal stenosis together accounted for the largest proportion of failures, exceeding adjacent segment disease, fixation instability, and pseudoarthrosis.

3.2. MRI Morphometric Screening of the Lumbar Foraminal Canal in Asymptomatic Adults

In the MRI screening cohort ($n = 500$, asymptomatic adults), foraminal canal volumes demonstrated level-dependent and side-dependent variability, with statistically significant differences across lumbar levels ($p < 0.001$). The mean foraminal canal volume increased progressively from the upper to lower lumbar spine (L1–L2 $\rightarrow$ L5–S1), while the percentage of nerve occupancy decreased inversely, indicating greater spatial reserve in caudal levels. These relationships are illustrated in Figure 4A, which plots mean foraminal volume by spinal level, and Figure 4B, showing the inverse relationship between foraminal volume and nerve occupancy percentage.

Interobserver agreement was excellent for foraminal volume and good for nerve occupancy. The ICC for Vforamen was 0.91 (95% CI, 0.88–0.94), while the ICC for nerve occupancy was 0.88 (95% CI, 0.83–0.92). Intraobserver repeatability was similarly high, with ICC values of 0.95 (95% CI, 0.92–0.97) for Vforamen and 0.92 (95% CI, 0.88–0.95) for occupancy (Table 1). The standardized measurement workflow demonstrated good to excellent reproducibility across the principal morphometric parameters. Interobserver agreement was excellent for foraminal volume and good for nerve occupancy. Intraobserver repeatability was consistently high, supporting the internal reliability of the measurement protocol. These findings support the internal reproducibility of the standardized measurement workflow.

A consistent but clinically modest trend toward larger left-sided foraminal volumes was observed across levels. This asymmetry did not translate into clinical symptoms in the reference population and was interpreted as a physiological anatomical variation rather than a pathological marker.

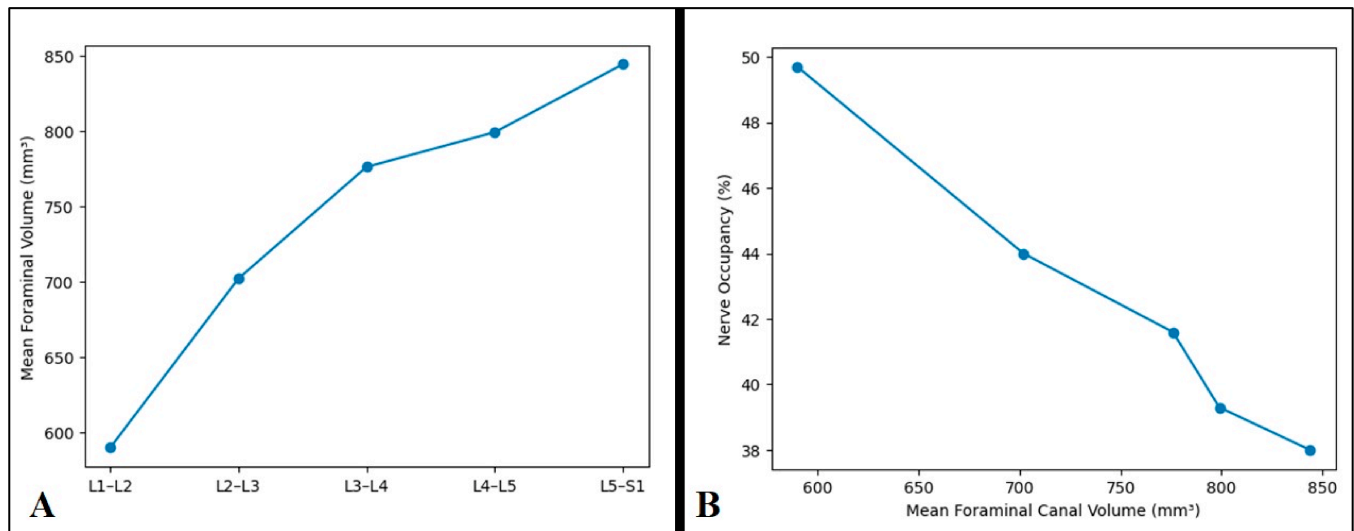


Figure 4. (A) Normative foraminal canal volume by lumbar level in asymptomatic adults. MRI-based morphometric screening ($n = 500$) demonstrated a progressive increase in foraminal canal volume from the upper to lower lumbar spine. Differences between levels were statistically significant ($p < 0.001$). (B) Inverse relationship between foraminal canal volume and nerve occupancy in asymptomatic adults. As the foraminal canal volume increases from upper to lower lumbar levels, the proportion of the canal occupied by the nerve root decreases. This anatomical relationship reflects increasing spatial reserve at caudal lumbar levels and supports the biological plausibility of volume-based stenosis thresholds.

Table 1. Interobserver and intraobserver reproducibility of foraminal morphometric measurements.

Parameter	Interobserver ICC	95% CI	Intraobserver ICC	95% CI
Foraminal long-axis diameter, a	0.92	0.89–0.95	0.95	0.92–0.97
Foraminal short-axis diameter, b	0.90	0.86–0.93	0.94	0.90–0.96
Foraminal depth, h	0.87	0.82–0.91	0.91	0.87–0.94
Foraminal volume	0.91	0.88–0.94	0.95	0.92–0.97
Nerve volume proxy	0.86	0.80–0.90	0.90	0.85–0.93
Nerve occupancy	0.88	0.83–0.92	0.92	0.88–0.95

ICC, intraclass correlation coefficient, and CI, confidence interval. ICC values were calculated using a two-way random-effects model with absolute agreement. Intraobserver repeatability was assessed in a randomly selected subset after a minimum two-week washout period.

3.3. Outcomes of Interventional Therapy in Chronic Vertebrogenic Pain ($n = 463$)

The dominant pain substrates identified through diagnostic blockades are summarized in Figure 5:

- Sacroiliac joint-related pain: 46.9%.
- Radicular pain: 20.9%.
- Discogenic pain: 11.4%.
- Facet-mediated pain: 10.4%.
- Myofascial pain: 10.4%.

This distribution underscores the multifactorial nature of chronic vertebrogenic pain and explains the limited specificity of symptoms for isolated foraminal stenosis.

Following selective blockades and radiofrequency denervation:

- Radiculopathy regressed in 44.7% of patients.
- Facet-mediated pain improved in 44.0%.
- Median pain relief duration was 3–6 months.

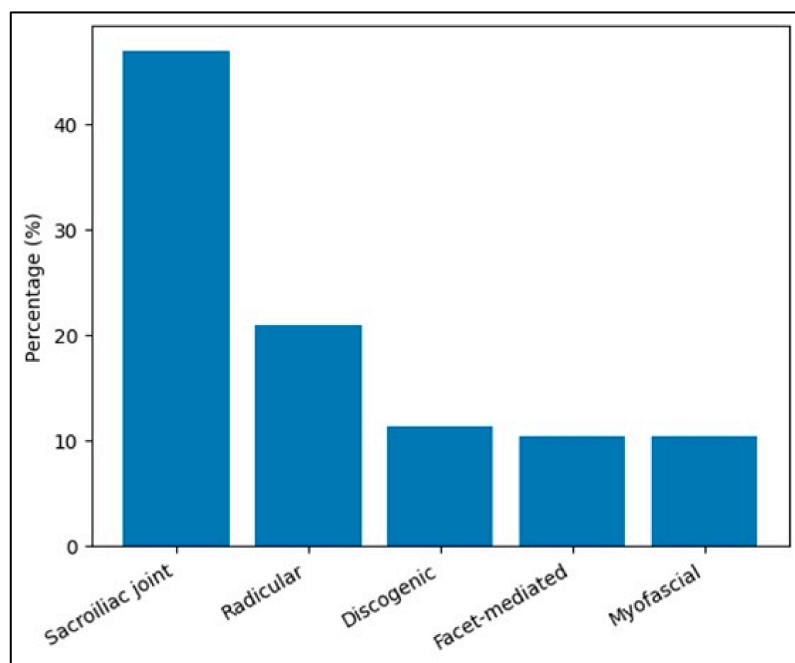


Figure 5. Distribution of dominant pain generators in patients with chronic vertebrogenic pain syndrome. Sacroiliac joint-related pain was the most prevalent pain generator (46.9%), followed by radicular pain (20.9%), discogenic pain (11.4%), facet-mediated pain (10.4%), and myofascial pain (10.4%), highlighting the multifactorial nature of chronic vertebrogenic pain.

Oswestry Disability Index (ODI) dynamics after interventional therapy are shown in Figure 6. Significant improvement was observed at 6 months (all $p < 0.001$), with partial decline toward baseline between 6 and 12 months. By 12 months, 55.3% of patients experienced recurrence of clinically significant pain, requiring escalation to surgical treatment. These findings defined the reasonable upper limit of interventional therapy in this population.

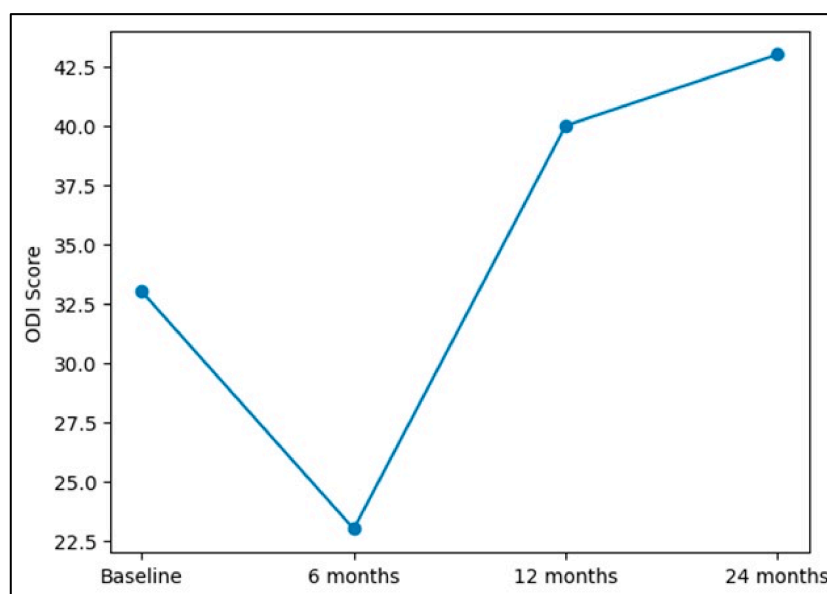


Figure 6. Oswestry Disability Index (ODI) dynamics after interventional therapy. Interventional treatment resulted in a significant reduction in disability at 6 months. However, a progressive decline in functional status was observed at 12 and 24 months, reflecting the limited durability of interventional therapy in patients with underlying foraminal stenosis.

3.4. Surgical Outcomes in Algorithm-Guided Foraminal Stenosis ($n = 256$)

All surgical strategies resulted in a statistically significant increase in foraminal canal volume ($p < 0.001$). The magnitude of volumetric expansion differed by technique, including endoscopic decompression (+29.9%), microsurgical decompression (+48.1%), TLIF (+67.0%), and ALIF/arthroplasty (+73.3%) (Figure 7). Despite larger volumetric gains with fusion-based techniques, excessive decompression did not correlate with superior long-term quality-of-life outcomes.

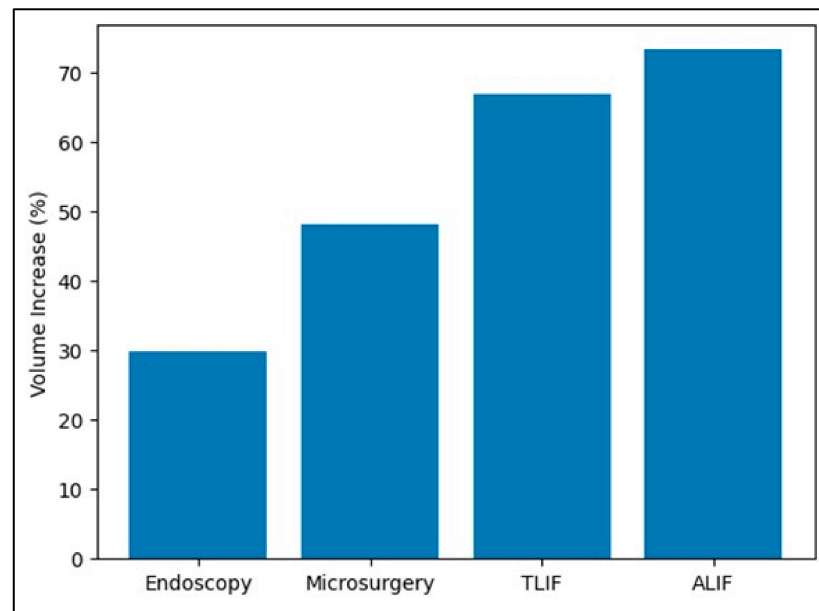


Figure 7. Increase in foraminal canal volume according to surgical technique. All surgical approaches produced statistically significant foraminal expansion ($p < 0.001$). Indirect decompression techniques (ALIF, TLIF) achieved the largest volumetric gains; however, greater expansion did not correlate with superior long-term clinical outcomes.

3.5. Comparative Outcomes: Endoscopic Decompression vs. ALIF

3.5.1. Pain and Functional Recovery

Both groups demonstrated significant improvement in VAS, ODI, and SF-36 scores over time. Endoscopic decompression achieved faster early leg pain relief (VAS leg, $p < 0.001$ at 6 and 12 months). ALIF resulted in superior long-term back pain control (VAS back, $p < 0.001$ at 12 and 24 months). At 24 months, pain levels were clinically equivalent between groups, indicating that procedure selection influences pain profile rather than absolute outcome.

3.5.2. Quality of Life

ODI and SF-36 PH/MH scores converged by 24 months, with no statistically significant differences in global health perception. ALIF showed a trend toward better ODI scores at late follow-up, reflecting improved segmental biomechanics.

3.6. Comparative Outcomes: Microsurgical Decompression vs. TLIF

Early postoperative recovery favored microsurgical decompression, with lower surgical morbidity and faster functional improvement at 6 months. At 12 and 24 months, microsurgical decompression demonstrated higher SF-36 PH and MH scores ($p < 0.001$). TLIF provided more durable back pain control, particularly in patients with preoperative instability.

At long-term follow-up (>24 months), patients treated with microsurgical decompression showed a higher incidence of recurrent monoradicular pain, consistent with delayed segmental instability.

3.7. Validation of the Volume-Based Diagnostic and Therapeutic Algorithm

Application of the algorithm integrating clinical severity, Lee grade [1], foraminal volume, and motion segment stability resulted in 72.3% improvement in SF-36 MH, 66.4% improvement in SF-36 PH, and 66.8% improvement in ODI, confirming that volume-guided stratification improves alignment between pathology, treatment choice, and patient-reported outcomes.

4. Discussion

Contemporary evidence supports a phenotype-driven interpretation of the present findings: imaging space creation is necessary for symptom relief, but the durability of benefit is governed by biomechanics, instability, and pain-generator overlap. A central observation is the nonlinear relationship between early morphometric expansion and long-term PROM superiority, a pattern that is consistent with the broader degenerative-lumbar literature on construct selection, indication discipline, and long-horizon tradeoffs [6,7,12–15].

The main finding of this study is that postoperative foraminal expansion alone does not fully explain long-term clinical outcomes. Larger volumetric gains were achieved with fusion-based or indirect decompression procedures, but superior morphometric expansion did not translate linearly into better disability or quality-of-life scores. This supports a phenotype-driven interpretation of LFS: the appropriate procedure depends not only on the amount of foraminal narrowing, but also on clinical concordance, pain-generator profile, segmental stability, and the mechanical reducibility of stenosis.

The largest volumetric gains were observed with indirect or fusion-based strategies, yet long-term patient-reported outcomes did not scale linearly with the amount of foraminal enlargement. This fits the concept that indirect decompression is fundamentally a mechanical correction—restoring disk height, foraminal height, and tensioning soft tissues—rather than a direct, focal neural decompression [16,17]. The effectiveness of indirect decompression has been repeatedly demonstrated across interbody paradigms where height restoration can expand neural corridors and relieve symptoms without extensive posterior bone work [18–20]. However, the same evidence base emphasizes variability: indirect decompression is most reliable when stenosis is reducible (height-dependent) and less reliable when stenosis is fixed (dense osteophyte/facet overgrowth, rigid collapse, or severe tethering) [21,22]. That variability offers a coherent explanation for why larger average postoperative volume gains do not automatically translate into uniformly superior long-term disability or quality-of-life scores.

This also clarifies the comparative clinical trajectories seen between indirect strategies and targeted decompression: when symptoms are driven by collapse-related foraminal compromise and segmental mechanics, procedures that restore height can produce durable back-pain control and functional recovery even if early radicular relief is not as immediate as with direct decompression [23,24]. Conversely, when the compressive substrate is focal and predominantly foraminal/extraforaminal, the clinical “signal” can be captured with less global remodeling, provided stability is preserved and decompression is sufficient rather than maximal [25,26]. Postoperative foraminal expansion remains an important therapeutic objective, particularly in severe fixed stenosis, where even modest increases in foraminal capacity may relieve mechanical irritation of the exiting nerve root. However, the present data suggest that the clinical value of volumetric gain depends on the underlying phenotype. In collapse-dominant or unstable segments, volume restoration may be

most effective when combined with biomechanical correction [25]. In stable focal stenosis, sufficient targeted decompression may provide meaningful relief without requiring maximal volumetric expansion. Thus, volumetric gain should be interpreted as necessary in selected patients, but not as the only determinant of long-term outcome. The endoscopic literature consistently shows meaningful improvements in pain and function with acceptable complication profiles when patients are selected appropriately [27–29]. However, comparative syntheses often report high heterogeneity and no universal superiority of endoscopic foraminotomy over fusion-based strategies, largely because the phenotypes treated differ: endoscopy is preferentially applied to stable segments and focal stenosis, whereas fusion is overrepresented in cases with collapse, instability, or multicomponent stenosis [30]. This is precisely the environment in which a quantitative foraminal capacity layer can add value—reducing reliance on purely qualitative impressions and helping discriminate “borderline” stenosis from clinically capacity-limiting disease in otherwise Schizas A–B canals.

Routine MRI is usually acquired in the supine unloaded position, which may underestimate foraminal compromise in patients whose stenosis becomes more pronounced during standing, lumbar extension, axial loading, or segmental motion. This limitation is particularly relevant in dynamic foraminal stenosis, degenerative spondylolisthesis, disk height collapse, and borderline instability. Future studies should evaluate the proposed volumetric and occupancy metrics using upright MRI, axial-loaded MRI, positional MRI, or flexion-extension imaging to determine whether dynamic measurements improve the prediction of symptoms and treatment response.

The proposed elliptical-cylinder model should be understood as a pragmatic morphometric approximation rather than a complete anatomical reconstruction of the lumbar foramen. The true foramen has irregular boundaries, and its geometry may be altered by osteophytes, facet hypertrophy, disk collapse, postoperative scarring, or prior decompression. Although this simplified model improves feasibility and reproducibility in routine MRI/CT workflows, it may underrepresent complex asymmetric encroachment or postoperative distortion. Cross-center reproducibility may also be influenced by slice thickness, scanner protocol, availability of oblique-axial reconstructions, and segmentation software. In practical use, the algorithm should not rely on a single morphometric number. Treatment selection was based on the five following sequential checks: (1) clinical-radiological concordance; (2) Lee foraminal stenosis grade; (3) static foraminal volume and nerve occupancy; (4) segmental stability; and (5) dominant pain generator assessed clinically and, when indicated, through diagnostic blocks. Patients with mild-to-moderate foraminal narrowing, low occupancy, and nonconcordant symptoms were directed toward continued nonoperative or interventional management. Patients with concordant radiculopathy, stable segments, and focal foraminal compromise were considered for targeted decompression. Patients with collapse-dominant stenosis and preserved posterior elements were considered for indirect decompression. Patients with instability, advanced collapse, spondylolisthesis, or anticipated destabilizing decompression were considered for decompression–stabilization.

Decision-making studies further support the premise that procedure selection is influenced by multidimensional factors (instability assessment, imaging interpretation, training environment, surgeon preference and biomaterials) rather than by any single imaging sign [31–33]. A structured, reproducible workflow (grading + volume/occupancy + stability thresholds) can therefore serve as a de-biasing mechanism that narrows unwarranted practice variation, particularly where technological adoption is uneven.

4.1. Decompression Alone vs. Decompression Plus Fusion: Stability Remains the Hinge Variable

Randomized evidence cautions against indiscriminate fusion in lumbar stenosis populations and reinforces the need for indication discipline. At the same time, degenerative spondylolisthesis trials and longitudinal observational evidence indicate that subgroups with mechanical instability can benefit from stabilization, with different tradeoffs in morbidity and reoperation patterns [34]. The present comparative trajectories are consistent with that high-level signal: where stability is preserved, and decompression can be accomplished without destabilizing resection, decompression-only strategies can yield excellent functional and mental-health recovery; where instability is present or iatrogenic destabilization is expected, decompression–stabilization can provide more durable back-pain control and reduce late recurrence related to progressive collapse.

This stability-dependent durability is also congruent with foundational biomechanical constructs that treat instability as a failure of the stabilizing system rather than a pure narrowing problem, with time-dependent progression when the segment remains mechanically compromised [35]. In practical terms, the data support a “minimum effective decompression” principle in stable segments and a “mechanics-first” principle in unstable segments—two different goals that should not be judged by the same yardstick.

4.2. Indirect Decompression Literature After 36: Why “Reducibility” and Failure-to-Indirect-Decompress Matter

Beyond general support for indirect decompression, more recent comparative and predictor-focused studies sharpen the selection logic. Work comparing indirect approaches with direct posterior techniques in severe stenosis underscores that indirect decompression can succeed in carefully chosen patients but is not universally sufficient—particularly when stenosis is rigid, or symptoms are driven by fixed bony encroachment [36]. Mechanistic investigations of indirect decompression further show that the degree of neural corridor expansion varies across individuals and depends on baseline anatomy and the capacity for ligamentotaxis and height restoration [37]. Predictor models emphasize that preoperative characteristics help identify who will achieve meaningful indirect decompression, reinforcing that an “indirect-first” strategy should be conditional rather than routine [38]. Selection criteria proposed for LLIF-type indirect decompression highlight practical markers of reducibility and also point to failure modes such as subsidence or insufficient restoration, which can blunt the decompressive effect over time [39]. Additional evidence indicates that a subset of patients will require staged or rescue posterior decompression after indirect fusion when symptoms persist despite radiographic changes, emphasizing that postoperative morphology and symptoms do not always couple tightly in rigid disease [40,41]. Reports of indirect decompression failure in contemporary series further reinforce the importance of preoperative phenotype and the need for transparent escalation pathways when indirect correction is incomplete [42]. These data map closely onto the observed dissociation between large average volume gains and uniform long-term PROM dominance: the mechanism works best when it is used for the phenotype it is designed to treat.

4.3. Long-Horizon Tradeoffs: Adjacent Segment Pathology and Why Avoiding Fusion Maximalism Remains Rational

Even when fusion produces large early morphometric gains, long-horizon outcomes must incorporate the risk of adjacent segment degeneration/disease and other fusion-related tradeoffs [43–45]. The adjacent segment literature consistently demonstrates that ASD is a real, cumulative phenomenon following lumbar arthrodesis, while also distinguishing radiographic degeneration from symptomatic disease [46–51]. Park et al. [47] and Harrop et al. [48] synthesize that ASD risk is real and cumulative after lumbar fusion, while also emphasizing that not all radiographic adjacent degeneration becomes symptomatic

disease. Ghiselli et al. [50] provide classic longitudinal estimates for adjacent segment degeneration after lumbar fusion. Conversely, motion-preserving approaches may reduce adjacent-level radiographic change in selected patients; Zigler et al. [52] reported 5-year adjacent-level degenerative changes comparing total disk replacement vs. fusion. Our “volume gain $\neq$ best outcome” finding supports a conservative interpretation: fusion should be reserved for patients whose pain generator is mechanical/unstable because any unnecessary fusion risks exchanging a short-term win for a long-term adjacent-level liability. These long-horizon considerations support a conservative interpretation: fusion should be reserved for segments where mechanical instability or collapse-dominant pathology is central to the symptom generator, rather than used reflexively to maximize immediate morphometric change.

4.4. Interventional Durability and the Role of Structured Temporization

The interventional evidence base supports the role of carefully selected facet and SIJ interventions as diagnostic and therapeutic tools [53–55]. However, durability limits are well recognized, and guideline-consistent practice emphasizes using interventions to clarify phenotype and to avoid premature surgery when the dominant pain generator is extraforaminal. When concordant radiculopathy persists despite appropriate temporization, escalation to structural correction becomes mechanistically coherent rather than preference-driven [10]. This logic is strengthened when measurement is standardized and symptom-imaging concordance is explicit. Our structured algorithm has a quality/systems implication. Brodeur et al. [24] reported that surgeon volume is associated with complication rates after lumbar fusion, reinforcing that outcomes are influenced by system factors, not only by technique selection. A key advantage of objective, reproducible stratification (Lee grade + volume/occupancy + stability) is that it can reduce unwarranted variation, standardize escalation thresholds, and potentially improve outcomes across practice environments, especially where surgeon experience with one approach is uneven. The proposed volumetric framework should be interpreted as complementary to Lee grading rather than as a replacement. Lee grading remains practical and clinically useful because it captures perineural fat obliteration and nerve root deformation. However, qualitative grades may group together patients with different degrees of residual spatial reserve. Foraminal volume provides an estimate of available canal capacity, whereas nerve occupancy expresses the proportion of that capacity occupied by the exiting root. Therefore, two patients with the same Lee grade may differ in occupancy burden, level-specific reserve, and vulnerability to dynamic collapse. This may explain why a combined framework incorporating Lee grade, volume, occupancy, and stability status may provide more granular stratification than qualitative grade alone.

Outcomes in fusion surgery are shaped not only by technique but also by system factors such as surgeon volume and disparity-related variables [16–22]. Technology-driven variability in training and practice patterns can further widen outcome heterogeneity and complicate comparisons across centers [6,53]. In that environment, reproducible stratification (qualitative grade + quantitative capacity + stability) becomes more than an academic contribution: it provides a framework for auditability, cross-center calibration, and transparent escalation thresholds—especially important in institutions where the case mix includes both focal stenosis and mechanically complex collapse/instability phenotypes.

4.5. Limitations

Several limitations should be emphasized. First, this was a single-center observational study with retrospective components. Therefore, the findings support association and

internal framework development rather than causal inference. The proposed algorithm should not be interpreted as a definitive clinical rule.

Second, treatment allocation was not randomized. Patients selected for endoscopic decompression, microsurgical decompression, indirect decompression, or fusion-based stabilization differed in baseline anatomy, degeneration, stability, and pain phenotype. This creates confounding by indication. Although multivariable adjustment was performed, residual confounding from unmeasured variables such as bone quality, sagittal balance, psychosocial status, rehabilitation exposure, surgeon preference, and patient expectations may persist.

Third, the four-cohort architecture strengthens the breadth of the framework but introduces selection at several levels, including imaging referral, eligibility for interventional therapy, response-based escalation, surgical candidacy, and follow-up completion. Patients who crossed from interventional therapy to surgery may represent a more treatment-resistant subgroup, limiting direct generalizability.

Fourth, the volumetric formula is based on a static elliptical-cylinder approximation and cannot fully capture irregular foraminal anatomy, asymmetric osteophytic encroachment, postoperative scarring, or dynamic three-dimensional deformation. Supine MRI may underestimate foraminal narrowing during standing, extension, axial loading, or segmental motion. Future studies should evaluate upright MRI, axial-loaded MRI, positional MRI, dynamic imaging, and patient-specific computational modeling.

Fifth, missing data and loss to follow-up may introduce attrition bias. Although complete-case analysis and imputation-based sensitivity analyses were used according to the proportion of missing PROM data, patients with persistent symptoms or complications may be less likely to return for long-term follow-up.

Finally, the algorithm was internally evaluated only. External validation in independent cohorts and prospective multicenter comparison against standard qualitative decision-making are required before broad implementation.

5. Conclusions

LFS has long been managed at the intersection of subjective symptom interpretation and qualitative imaging descriptors. This study advances the field by introducing a structured, volume-integrated framework that operationalizes foraminal space as a measurable, reproducible variable—linking anatomy, mechanical stability, and treatment selection within a single decision pathway.

By integrating Lee grading [1], quantitative foraminal volume, nerve occupancy, and segmental stability, we demonstrate that treatment success in LFS is not determined by the magnitude of decompression alone, but by the precision of phenotypic matching. Indirect decompression, endoscopic foraminotomy, microsurgical decompression, and fusion-based stabilization each have a rational role when aligned with the biomechanical context rather than applied reflexively.

The data suggest that volumetric stratification improves concordance between pathology and intervention, reduces misclassification of borderline cases, and provides an objective parameter that can be tracked pre- and post-operatively. Importantly, greater volumetric expansion did not equate to superior long-term quality-of-life outcomes, reinforcing that surgical adequacy—not maximalism—should guide intervention.

This study proposes an internally evaluated, volume-integrated framework for lumbar foraminal stenosis that combines Lee grade, static foraminal volume, nerve occupancy, clinical concordance, interventional response, and segmental stability.

In this single-center observational cohort, the framework was associated with clinically meaningful improvement across treatment pathways and suggested that procedure selec-

tion may be better guided by phenotype matching than by foraminal expansion alone. The findings suggest that treatment success depends not only on the magnitude of foraminal expansion, but on matching the procedure to the anatomical and biomechanical phenotype of the affected segment. The proposed model should be interpreted as a pragmatic decision-support framework rather than a definitive clinical rule.

External validation, prospective multicenter testing, and comparison with standard decision-making pathways are required to determine whether this approach improves patient selection, reduces unnecessary fusion, decreases revision surgery, and improves long-term patient-reported outcomes. Although external validation is required, this framework represents a step toward a more quantitative, stability-aware, and phenotype-driven paradigm in the management of LFS, moving the field from descriptive grading toward measurable decision intelligence.

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Conflicts of Interest: The authors declare no conflicts of interest.

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