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Decompression of Lumbar Central Spinal Canal Stenosis Following Minimally Invasive Transforaminal Lumbar Interbody Fusion

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Study Design: This was a retrospective clinical series.

Objective: The objective of this study was to evaluate radiologic changes in central spinal canal dimensions following minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) with placement of a static or an expandable interbody device.

Summary of Background Data: MIS-TLIF is used to treat lumbar degenerative diseases and low-grade spondylolisthesis. MIS-TLIF enables direct and indirect decompression of lumbar spinal stenosis, with patients experiencing relief from radiculopathy and neurogenic claudication. However, the effects of MIS-TLIF on the central spinal canal are not well-characterized.

Materials and Methods: We identified patients who underwent MIS-TLIF for degenerative lumbar spondylolisthesis and concurrent moderate to severe spinal stenosis. We selected patients who had both preoperative and postoperative magnetic resonance imaging (MRI) and upright lateral radiographs of the lumbar spine. Measurements on axial T2-weighted MRI scans include anteroposterior and transverse dimensions of the dural sac and osseous spinal canal. Measurements on radiographs include disk height, neural foraminal height, segmental lordosis, and spondylolisthesis. We made pairwise comparisons between each of the central canal dimensions and lumbar sagittal segmental radiologic outcome measures relative to their corresponding preoperative values. Correlation coefficients were used to quantify the association between changes in lumbar sagittal segmental parameters relative to changes in radiologic outcomes of central canal dimensions. Statistical analysis was performed for "all patients" and further stratified by interbody device subgroups (static and expandable).

Results: Fifty-one patients (age 60.4 y, 68.6% female) who underwent MIS-TLIF at 55 levels (65.5% at L4–L5) were included in the analysis. Expandable interbody devices were used in 45/55 (81.8%) levels. Mean duration from surgery to postoperative MRI scan was 16.5 months (SD 11.9). MIS-TLIF was associated with significant improvements in dural sac dimensions (anteroposterior +0.31 cm, transverse +0.38 cm) and osseous spinal canal dimensions (anteroposterior +0.16 cm, transverse +0.32 cm). Sagittal lumbar segmental parameters of disk height (+0.56 cm), neural foraminal height (+0.35 cm), segmental lordosis (+4.26 degrees), and spondylolisthesis (−7.5%) were also improved following MIS-TLIF. We did not find meaningful associations between the changes in central canal dimensions relative to the corresponding changes in any of the sagittal lumbar segmental parameters. Stratified analysis by interbody device type (static and expandable) revealed similar within-group changes as in the overall cohort and minimal between-group differences.

Conclusions: MIS-TLIF is associated with radiologic decompression of neural foraminal and central spinal canal stenosis. The mechanism for neural foraminal and central canal decompression is likely driven by a combination of direct and indirect corrective techniques.

Key Words: minimally invasive lumbar fusion, transforaminal lumbar interbody fusion, MIS-TLIF, lumbar spinal canal stenosis, indirect decompression

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Neurogenic claudication due to lumbar spinal stenosis and degenerative spondylolisthesis is a common source of low back and leg pain, impaired walking, and physical disability.[1] The traditional approach to operative management involves

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laminectomy and partial facetectomy, with or without concomitant arthrodesis,[2,3] to directly decompress the central spinal canal and neural foramina.[1]

Minimally invasive techniques in spinal surgery (MISS) have been introduced that achieve similar decompression through smaller incisions, less muscle dissection and disruption, and limited removal of the laminae and facet joints.[4] MISS leverages direct and indirect corrective techniques to decompress symptomatic neural elements using less bony resection and maintaining midline ligamentous structures.[5] Vertebral interbody distraction, spondylolisthesis reduction, and fixation restores normal disk height, interpedicular distance, and segmental lordosis, thereby widening the neural foramina and epidural space.[5,6] In fact, indirect decompression achieved through *anterior*[7–9] and *lateral*[10–13] lumbar interbody fusion provides sustained clinical resolution of preoperative radiculopathy and neurogenic claudication, which correlate with postoperative increases in neural foraminal and central canal areas.

The posterolateral-approach minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF) is increasingly used to treat lumbar degenerative spondylotic disease and low-grade spondylolisthesis.[14] Compared with open surgery, MIS-TLIF is associated with decreased operative blood loss, shorter lengths of stay, earlier mobilization, lower opioid use, and earlier return to work,[14–16] while maintaining comparable long-term clinical outcomes and fusion rates.[17,18] Indeed, MIS-TLIF achieves decompression of the affected nerve roots directly via discectomy and partial facetectomy, and indirectly via segmental realignment and disk height restoration with placement of an interbody device.[19–21] Beyond the limited facetectomy, additional posterior decompression is rarely performed. The extent to which the evidence for neural foraminal indirect decompression following MIS-TLIF can be extrapolated to central lumbar spinal canal stenosis, as is proposed with anterior and lateral lumbar interbody fusion, is not known.

The objective of this study is to evaluate the radiologic changes in central spinal canal dimensions and sagittal lumbar segmental parameters following MIS-TLIF in a series of patients with preoperative moderate to severe lumbar spinal stenosis.

MATERIALS AND METHODS

Patient Sample

This is a retrospective case series of adult patients who underwent MIS-TLIF at 1 or 2 adjacent lumbar levels (Fig. 1). The operations were performed at 1 of 2 academic medical centers (Washington University in St. Louis/Barnes-Jewish Hospital and Wayne State University/Henry Ford Hospital) between November 2014 and October 2018. Patients experienced symptoms of radiculopathy and concomitant lumbar spinal stenosis, including neurogenic claudication in 1 or both legs and low back pain, which did not improve with nonoperative management. The indications for surgery were lumbar spinal foraminal and central stenosis, with or without Meyerding[22] grades I/II degenerative spondylolisthesis and dynamic instability. Patients were included in the analysis who had both preoperative and postoperative magnetic resonance imaging (MRI) scans of the lumbar spine available for analysis.

Operative Intervention

All patients underwent MIS-TLIF with placement of an interbody device at the affected level(s), using the surgical technique as described by Hawasli et al,[19] Khalifeh et al,[21] and Massie et al.[20] Briefly, MIS-TLIF were performed on a modular ProAxis Jackson table (Mizuho), which allows reversible kyphotic flexion to facilitate wide exposure to the working access corridor. Under fluoroscopic guidance, 2 paramedian incisions were made over the selected pedicles, followed by sequential dilation, tubular retraction, ipsilateral facetectomy, and contralateral partial facetectomy and decortication. This was followed by discectomy, placement of the interbody device, and bilateral percutaneous pedicle screw fixation and rod instrumentation.

Patients underwent MIS-TLIF with placement of either a static or an expandable interbody device. The interbody device is placed at the anterior-most aspect of the disk space, which is packed with morselized autograft and/or allograft. Device type was uniform within the 2 subgroups, although varying sizes were used to accommodate individual anatomy. The static interbody devices consisted of a 'kidney bean'-shaped steerable implant with a poly-ether-etherketone material composition and built-in 0–5 degrees lordotic angle. The expandable interbody devices consisted of a steerable, "banana"-shaped, titanium expandable implant with a built-in 8–15 degrees lordotic angle that can be adjusted intraoperatively to allow desired distraction of the disk space and maximize segmental lordotic correction.

Direct bony decompression was achieved primarily via the limited facetectomy necessary for accessing the disk space for disk removal and placement of an interbody device. Additional posterior central canal decompression was *only rarely* performed in the setting of severe bony lateral recess stenosis.[21]

Clinical Information

We collected information on demographics, clinical characteristics, radiologic diagnoses, and details of the operative procedures available through chart review. We additionally collected the reasons for postoperative MRI scan acquisition, as it is not routine practice to obtain an MRI scan of the lumbar spine in a clinically improving or otherwise asymptomatic patient postoperatively.

Radiologic Outcome Measures

Lumbar central spinal canal dimensions were measured as described by Mamisch et al,[23] Kim et al,[9] and Zheng et al.[24] Computerized radiologic measurements were made on preoperative and postoperative T2-weighted MRI scans. The anteroposterior and transverse dimensions of each the dural sac and osseous spinal canal were measured manually at a single axial slice through the center of the disk at the affected level(s). The anteroposterior length of the spinal canal was measured from the posterior edge of the intervertebral disk space to the most posterior point of the bony canal in the axial plane. The transverse length of the osseous spinal canal was measured as the distance

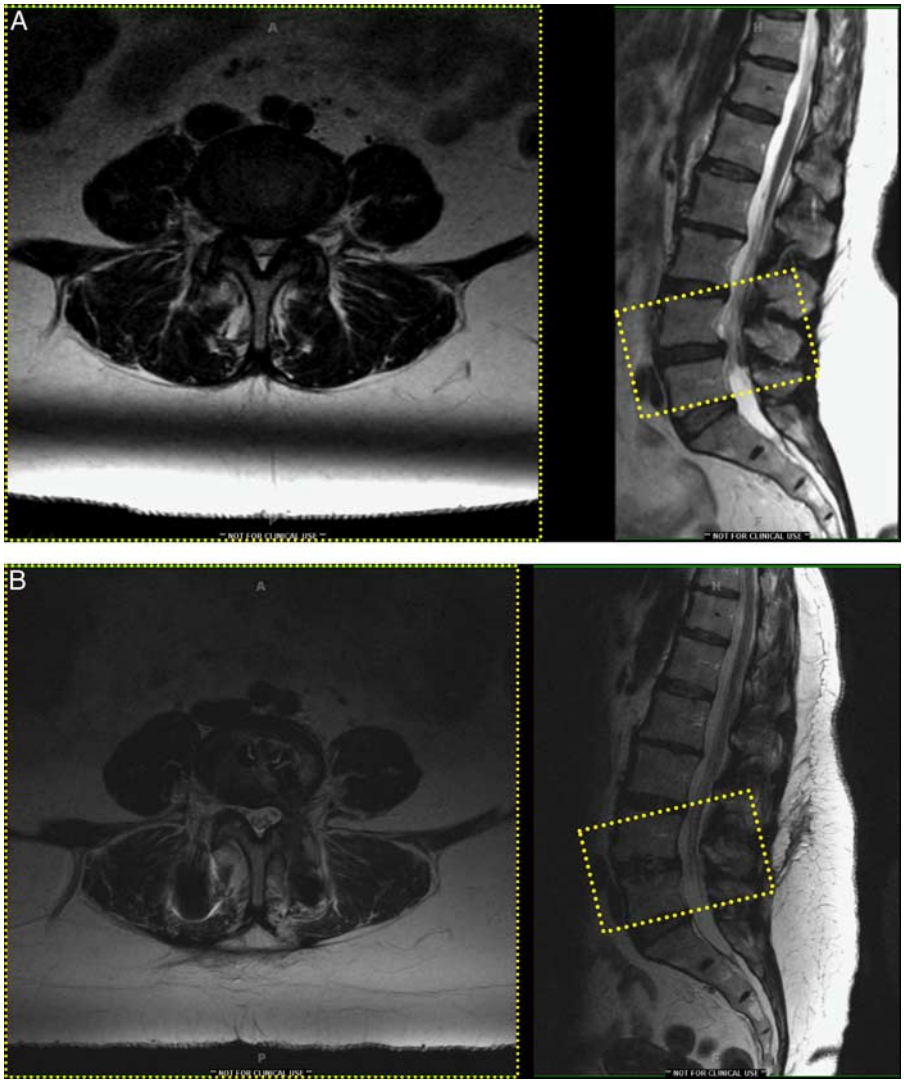

FIGURE 1. A, Axial and sagittal T2-weighted magnetic resonance imaging scan of a patient with symptomatic lumbar spinal stenosis due to a central disk bulge, thickened ligamentum flavum, and grade I spondylolisthesis at L4–L5. B, Postoperative T2-weighted magnetic resonance imaging scans demonstrate postsurgical changes at L4–L5 with decompression and widening of the central canal in the axial and midsagittal planes following minimally invasive transforaminal lumbar interbody fusion. Dotted boxes indicate the region of interest at L4-L5 and index level of surgery. full color online

between the lateral edges of the lateral recesses. The cross-sectional areas enclosed within each the dural sac and the osseous spinal canal were calculated using the formula for an ellipse (area = πab, where a and b are the major and minor radii). The dural sac/osseous spinal canal ratio was calculated for quantitative assessment of lumbar spinal canal stenosis.[24] A low anteroposterior or transverse dural sac/osseous spinal canal ratio indicates a greater degree of spinal canal stenosis with dural sac compression.

Sagittal segmental parameters were measured manually on digital full-length 36-inch upright lateral radiographs of the lumbar spine. Radiographic measurements were evaluated preoperatively and postoperatively at the time of follow-up closest to the postoperative MRI scan. Lumbar sagittal segmental parameters included disk height, neural foraminal height, segmental lordosis, and amount of spondylolisthesis at the affected level(s). Disk height was measured anteriorly at the fused segment, from the inferior endplate of the rostral vertebral body to the superior endplate of the caudal vertebral body. Neural foraminal height was measured on lateral radiographs as the maximum rostrocaudal distance of the intervertebral foramen.[25] Segmental lordosis was measured as the lateral Cobb angle at the superior and inferior endplates of the fused segment. The amount of listhesis was measured as the percentage offset (slip) of the vertebral body posterior wall relative to the adjacent caudal vertebral body.[26,27]

Statistical Analysis

Descriptive statistics were calculated to summarize demographics, clinical information, operative details, and

radiologic outcomes. Continuous variables are presented using means and SD. Categorical variables are presented using frequencies and percentages. Paired sample *t* tests were used to compare radiologic outcome measures following MIS-TLIF. We made pairwise comparisons between each postoperative dural sac dimensions, spinal canal dimensions, and sagittal lumbar segmental parameters relative to their corresponding preoperative values. Statistical analysis was performed for "all patients" and further stratified by interbody device subgroups (static and expandable).

In addition, we performed a bivariate (Pearson) correlation analysis to examine the changes in lumbar sagittal segmental parameters relative to changes in radiologic outcomes of central canal dimensions. Pearson correlation coefficients were calculated to quantify the association between the changes in each dural sac dimensions and osseous spinal canal dimensions relative to the corresponding changes in each disk height, neural foraminal height, segmental lordosis, and amount of spondylolisthesis. Correlation coefficients are interpreted as follows: 0.0–0.19 = very weak, 0.2–0.39 = weak, 0.4–0.59 = moderate, 0.6–0.79 = strong, and 0.8–1.0 = very strong.[28] Strong positive associations, or negative associations in the case of amount of spondylolisthesis, would provide evidence for a mechanism of predominant *indirect* decompression of the lumbar central spinal canal attributable to changes in sagittal segmental parameters.

A 2-sided P-value < 0.05 was considered statistically significant. All statistical analyses were performed using IBM SPSS Statistics v25 (SPSS Inc., Chicago, IL).

Ethical Oversight

The study was approved by our Institutional Review Board. Consent was waived as this is a retrospective review of cases.

RESULTS

Demographics, Clinical Information, and Operative Details

Of 190 patients who underwent MIS-TLIF at 196 levels during the study time frame, we identified 51 patients with 55 levels of MIS-TLIF who had both preoperative and postoperative MRI scans of the lumbar spine available for analysis (Table 1). The mean age at surgery was 60.4 years (SD 10.2, range: 33–77). The majority of procedures (36/55, 65.5%) were performed at L4–L5. Expandable interbody devices were used in 45/55 (81.8%) levels.

The mean duration from the surgical procedure to postoperative MRI scan was 16.5 months (SD 11.9, range 0.2–46.8). In our study sample, the reasons for acquiring a lumbar MRI during the postoperative period included new or recurrent symptoms of back and/or radicular pain (n = 41 patients) and factors unrelated to the initial surgery (n = 10). The obtained MRI scan provided supportive evidence for clinical concern for pseudarthrosis (6/51, 11.8%) and/or adjacent segment disease (9/51, 17.6%) requiring reoperation (15/51, 29.4%) with interval revision of the index level or extension of fusion.

Radiologic Outcomes: Dural Sac and Central Canal Dimensions

MIS-TLIF was associated with decompression of the lumbar central spinal canal as assessed by measurements of anteroposterior and transverse dural sac and osseous spinal canal dimensions on preoperative and postoperative MRI scans (Table 2, Fig. 2).

The mean anteroposterior dural sac diameter increased significantly from 1.1 cm (SD 0.3) preoperatively to 1.4 cm (SD 0.3) postoperatively [mean change: 0.31 cm; 95% confidence interval (CI): 0.26–0.37; $P < 0.001$]. The mean transverse dural sac diameter increased from 1.4 cm (SD 0.4) to 1.8 cm (SD 0.3) postoperatively (mean change: 0.38 cm; 95% CI: 0.3–0.5; $P < 0.001$). These dural sac measurements correspond to a mean relative increase in the anteroposterior axis of 28.2% and in the transverse axis of 27.1%. In addition, we observed significant postoperative increases in the anteroposterior (mean change: 0.16 cm; 95% CI: 0.1–0.2; $P < 0.001$) and transverse (mean change 0.32 cm; 95% CI: 0.2–0.4; $P < 0.001$) osseous spinal canal diameters.

The mean anteroposterior dural sac/osseous canal ratio increased from 71.2% (SD 15.2) preoperatively to 82.4% (SD 13.6) postoperatively (mean change: 11.2%; 95% CI: 7.6–14.8; $P < 0.001$). Similarly, the mean

TABLE 1. Demographic and Operative Characteristics of Patients Who Underwent MIS-TLIF With a Static or Expandable Interbody Device

Patient Characteristics	All Patients (N = 51 Patients)	Static Interbody Device (N = 9 Patients)	Expandable Interbody Device (N = 42 Patients)
No. MIS-TLIF levels	55	10	45
Age at surgery (range) (y)	60.4 (10.2) (33–77)	56.1 (10.7) (33–73)	61.3 (10.0) (34–77)
Preoperative BMI (kg/m^2)	28.5 (6.6)	27.1 (8.0)	28.8 (6.3)
Sex (female)	35 (68.6)	7 (77.8)	28 (66.7)
Preoperative spondylolisthesis			
Grade I or less	46 (83.6)	9 (90.0)	37 (82.2)
Grade II+	6 (10.9)	1 (10.0)	5 (11.1)
Missing	3 (5.5)	0 (0.0)	3 (6.7)
Preoperative radiologic diagnoses			
Spondylolisthesis	38 (69.1)	6 (60.0)	32 (71.1)
Disk bulge/central herniation	27 (49.1)	9 (90.0)	18 (40.0)
Foraminal disk herniation	13 (23.6)	5 (50.0)	8 (17.8)
Operative levels			
L2–L3	3 (5.5)	1 (10.0)	2 (4.4)
L3–L4	7 (12.7)	2 (20.0)	5 (11.1)
L4–L5	36 (65.5)	7 (70.0)	29 (64.4)
L5–S1	9 (16.4)	0 (0.0)	9 (20.0)
Duration from surgery to postoperative MRI (range) (mo)	16.5 (11.9) (0.2–46.8)	20.8 (15.3) (0.6–46.8)	15.5 (11.0) (0.2–37.3)

Values are presented as n (%) for categorical variables or mean (SD) for continuous variables.

BMI indicates body mass index; MIS-TLIF, minimally invasive transforaminal lumbar interbody fusion; MRI, magnetic resonance imaging.

TABLE 2. Central Canal Dimensions and Radiographic Lumbar Sagittal Segmental Parameters Reported Preoperatively and Postoperatively Following MIS-TLIF With a Static or an Expandable Interbody Device

	Preoperative				Postoperative			
Radiologic Outcomes	All Patients	Static Interbody Device	Expandable Interbody Device	Mean Difference Expandable Static (95% CI)	All Patients	Static Interbody Device	Expandable Interbody Device	Mean Difference Expandable Static (95% CI)
AP dural sac (cm)	1.1 (0.3)	1.1 (0.2)	1.1 (0.3)	0.01 (−0.2 to 0.2)	**1.4 (0.3)**	**1.4 (0.2)**	**1.4 (0.3)**	−0.01 (−0.2 to 0.2)
AP spinal canal (cm)	1.6 (0.3)	1.7 (0.2)	1.5 (0.3)	−0.2 (−0.4 to 0.01)	**1.7 (0.2)**	1.8 (0.2)	**1.7 (0.3)**	−0.1 (−0.3 to 0.1)
AP dural sac/spinal canal ratio (%)	71.2 (15.2)	62.9 (11.0)	73.0 (15.5)	10.1 (−0.3 to 20.6)	**82.4 (13.6)**	**78.6 (14.5)**	**83.2 (13.4)**	4.7 (−4.9 to 14.2)
Transverse dural sac (cm)	1.4 (0.4)	1.4 (0.3)	1.4 (0.4)	0.06 (−0.2 to 0.3)	**1.8 (0.3)**	**1.7 (0.3)**	**1.8 (0.3)**	0.1 (−0.1 to 0.4)
Transverse spinal canal (cm)	2.0 (0.4)	2.0 (0.2)	2.0 (0.4)	0.01 (−0.2 to 0.2)	**2.3 (0.4)**	2.1 (0.2)	**2.3 (0.5)**	0.2 (−0.1 to 0.4)
Transverse dural sac/spinal canal ratio (%)	73.3 (15.0)	70.2 (12.2)	74.0 (15.6)	3.9 (−6.7 to 14.4)	**80.4 (9.9)**	79.5 (7.7)	**80.6 (10.4)**	1.1 (−6.0 to 8.1)
Dural sac area (cm^2)	1.3 (0.6)	1.2 (0.3)	1.3 (0.6)	0.1 (−0.3 to 0.5)	**2.1 (0.7)**	**1.9 (0.5)**	**2.1 (0.7)**	0.2 (−0.3 to 0.6)
Spinal canal area (cm^2)	2.5 (0.7)	2.7 (0.4)	2.4 (0.8)	−0.3 (−0.7 to 0.1)	**3.1 (0.8)**	**3.1 (0.6)**	**3.1 (0.9)**	0.03 (−0.5 to 0.6)
Area dural sac/spinal canal ratio (%)	53.1 (18.1)	44.3 (11.9)	55.1 (18.8)	**10.8 (1.0–20.6)**	**66.3 (13.8)**	**62.5 (13.7)**	**67.1 (13.8)**	4.5 (−5.1 to 14.2)
Disk height (cm)	0.9 (0.3)	0.9 (0.3)	0.9 (0.3)	0.04 (−0.2 to 0.2)	**1.5 (0.3)**	**1.1 (0.2)**	**1.5 (0.3)**	**0.4 (0.2–0.6)**
Neural foraminal height (cm)	1.6 (0.5)	1.9 (0.3)	1.6 (0.5)	−0.3 (−0.6 to 0.03)	**1.9 (0.4)**	2.0 (0.3)	**1.9 (0.5)**	−0.1 (−0.4 to 0.2)
Segmental lordosis (deg.)	12.2 (8.8)	5.6 (3.3)	13.7 (9.0)	**8.1 (4.6–11.6)**	**16.5 (7.7)**	**9.9 (2.9)**	**18.0 (7.7)**	**8.1 (5.1–11.0)**
Spondylolisthesis (%)	12.8 (9.7)	11.1 (10.4)	13.2 (9.6)	2.1 (−4.8 to 9.0)	**5.1 (5.5)**	**4.5 (4.1)**	**5.2 (5.8)**	0.7 (−3.2 to 4.6)

Postoperative radiographic outcomes were recorded during follow-up closest to the time of magnetic resonance imaging acquisition.
Values presented as mean (SD) or mean difference (95% CI).
Bolded values indicate statistically significant differences ($P < 0.05$).
Paired samples *t* test was used to evaluate within-groups mean postoperative change in radiologic outcome measures relative to their corresponding preoperative values.
Unpaired samples *t* test was used to evaluate preoperative and postoperative between-group differences in radiologic outcome measures between patients who underwent MIS-TLIF with a static versus an expandable interbody device. All patients: N = 51 patients, 55 levels. Static interbody device: N = 9 patients, 10 levels. Expandable interbody device: N = 42 patients, 45 levels.
AP indicates anteroposterior; CI, confidence interval; MIS-TLIF, minimally invasive transforaminal lumbar interbody fusion.

transverse dural sac/osseous canal ratio from 73.3% (SD 15.0) to 80.4% (SD 9.9) (mean change: 7.0%; 95% CI: 2.7–11.4; $P = 0.002$).

Stratified analysis by interbody device type (static vs. expandable) revealed similar within-group postoperative changes as in the overall cohort. There were no significant between-group differences in preoperative and postoperative radiologic outcomes of central canal dimensions (Table 2).

Radiologic Outcomes: Disk Height, Neural Foraminal Height, Segmental Lordosis, and Spondylolisthesis

MIS-TLIF was associated with postoperative increases in index-level disk height, neural foraminal height, and segmental lordosis, and reductions in spondylolisthesis (Table 2, Fig. 3).

Mean disk height increased significantly from 0.9 cm (SD 0.3) preoperatively to 1.5 cm (SD 0.3) postoperatively (mean change: 0.56 cm; 95% CI: 0.46–0.66; $P < 0.001$). Similarly, there was a significant increase in neural foraminal height following surgery (mean change: 0.35 cm; 95% CI: 0.24–0.45; $P < 0.001$).

MIS-TLIF was associated with an increase in index-level segmental lordosis. The mean fused segment angle increased by 4.26 degrees (95% CI: 3.01–5.52; $P < 0.001$), from 12.2 degrees (SD 8.8) preoperatively to 16.5 degrees (SD 7.7) postoperatively.

There was a significant postoperative reduction in spondylolisthesis. Before surgery, 46/55 (83.6%) of operative levels had grade I spondylolisthesis. The mean percentage offset of 1 vertebral body over the adjacent segment decreased significantly following surgery, from 12.8% (SD 9.7) to 5.1% (SD 5.5) (mean change: −7.5%; 95% CI: −10.0 to −5.0; $P < 0.001$).

Stratified analysis by interbody device type (static vs. expandable) revealed similar within-group postoperative changes as in the overall cohort. There were no significant between-group differences in preoperative and postoperative radiologic outcomes of lumbar sagittal segmental parameters (Table 2).

There were no meaningful associations between the changes in dural sac dimensions (Table 3, Fig. 4) nor osseous spinal canal dimensions (Table 3, Fig. 5) relative to the corresponding changes in each disk height, neural foraminal height, segmental lordosis, and amount of spondylolisthesis.

DISCUSSION

Summary of the Findings

In summary, we provide radiologic evidence for neural foraminal and central canal decompression following MIS-TLIF with placement of an expandable interbody device in patients with degenerative lumbar spondylotic disease and concurrent moderate to severe spinal stenosis.

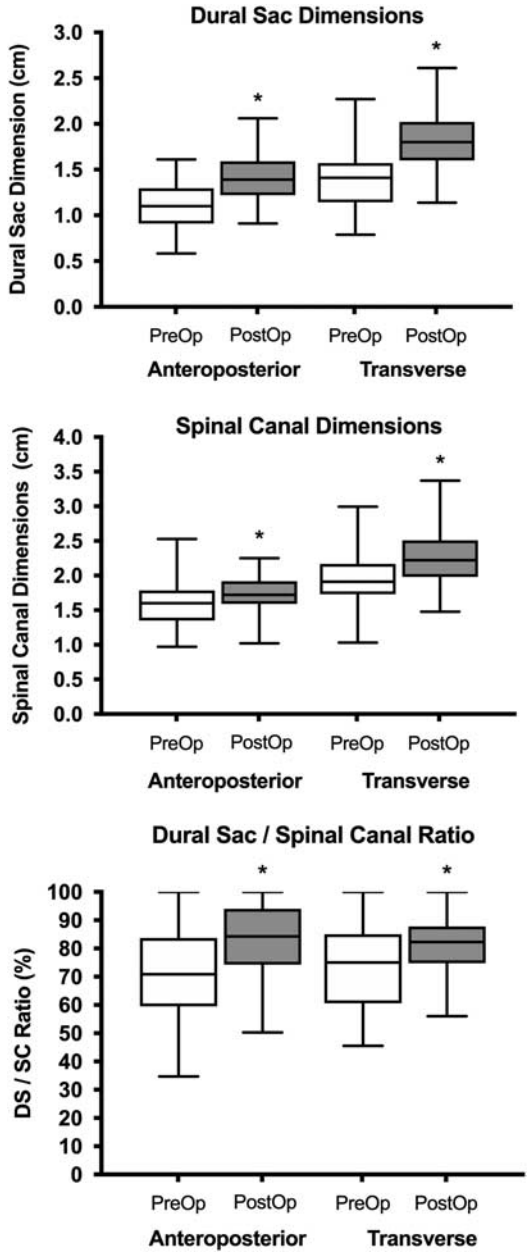

FIGURE 2. Anteroposterior and transverse dimensions of the dural sac and osseous spinal canal were measured on axial T2-weighted imaging at each operative level on the preoperative (preop) and postoperative (postop) magnetic resonance imaging studies. Data are presented for "all patients." Box and whisker plots (boxes extend from 25th to 75th percentiles and whiskers from minimum to maximum). *$P < 0.05$, paired samples t test postoperative versus preoperative.

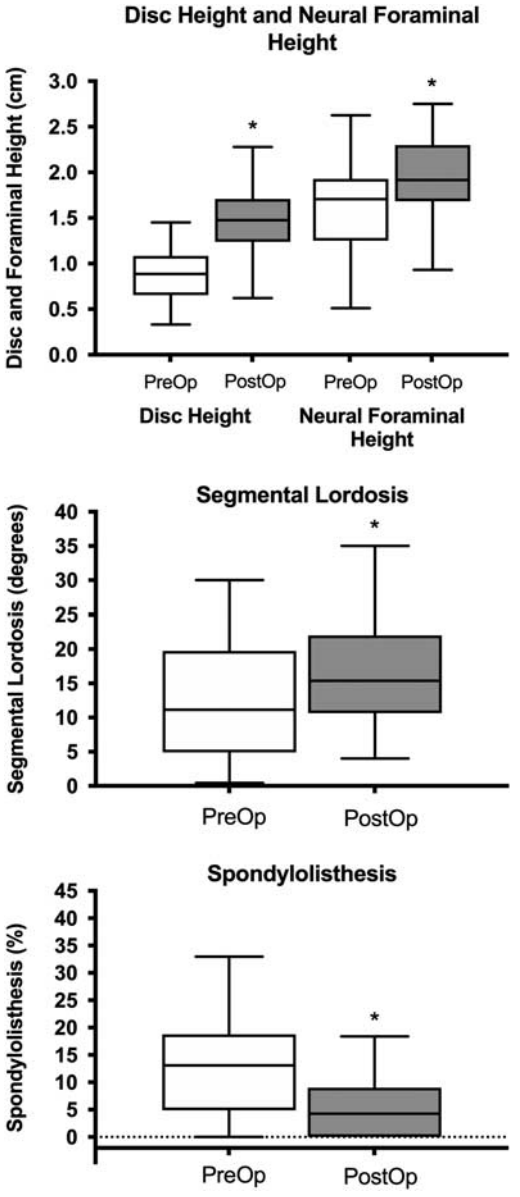

FIGURE 3. Lumbar sagittal segmental parameters of disk height, neural foraminal height, segmental lordosis, and amount of spondylolisthesis (percentage vertebral body offset) were measured at each operative level on upright lateral radiographs obtained preoperatively (preop) and postoperatively (postop). Data are presented for "all patients." Box and whisker plots (box extends from 25th to 75th percentiles, and whiskers from minimum to maximum). *$P < 0.05$, paired samples t test postoperative versus preoperative.

We observed significant improvements in dural sac dimensions (anteroposterior +0.31 cm, transverse +0.38 cm), osseous spinal canal dimensions (anteroposterior +0.16 cm, transverse +0.32 cm), and radiographic sagittal lumbar segmental parameters of disk height (+0.56 cm), neural foraminal height (+0.35 cm), segmental lordosis (+4.26 degrees), and spondylolisthesis (−7.5%). We also observed significant improvements in anteroposterior (+11.2%) and transverse (+7.04%) dural sac/osseous spinal canal ratios following surgery, indicating relative decompression of the dural sac. Stratified analysis by interbody device type (static vs. expandable) revealed similar within-group findings as in the overall cohort and minimal between-group differences.

TABLE 3. Pearson Correlation Coefficients Calculated to Quantify the Association Between the Changes in Each Anteroposterior and Transverse Dural Sac Dimensions and Osseous Spinal Canal Dimensions Against the Corresponding Changes in Each Disk Height, Neural Foraminal Height, Segmental Lordosis, and Amount of Spondylolisthesis

Pearson Correlations	Change in Disk Height	Change in Neural Foraminal Height	Change in Segmental Lordosis	Change in Amount of Spondylolisthesis
Change in AP dural sac				
All patients	−0.12	0.01	−0.12	0.12
Static interbody devices	−0.47	**−0.74**	−0.08	0.26
Expandable interbody devices	−0.08	0.25	−0.13	0.09
Change in AP spinal canal				
All patients	−0.15	0.19	−0.02	−0.07
Static interbody devices	0.06	−0.26	0.39	**−0.78**
Expandable interbody devices	−0.25	0.23	−0.05	0.03
Change in transverse dural sac				
All patients	0.17	−0.10	0.15	0.17
Static interbody devices	−0.21	−0.47	−0.30	0.40
Expandable interbody devices	0.23	−0.01	0.25	0.11
Change in transverse spinal canal				
All patients	0.10	0.03	0.08	0.06
Static interbody devices	−0.15	−0.42	−0.17	0.06
Expandable interbody devices	0.05	0.06	0.11	0.07

Correlation analysis is further stratified by static and expandable interbody device subgroups.
Bolded values indicate significant correlations at $P < 0.05$.
AP indicates anteroposterior.

We did not find meaningful associations between the changes in dural sac dimensions nor osseous spinal canal dimensions relative to the corresponding changes in each of the sagittal lumbar segmental parameters. The correlation analysis *does not* provide definitive evidence for a mechanism of central canal decompression achieved primarily via indirect techniques of interbody distraction, disk height restoration, and reduction of the spondylolisthesis. Rather, the mechanism of lumbar central spinal canal decompression is likely driven by a combination of direct and indirect techniques.

Findings in Context: Lateral Access Lumbar Interbody Fusion

Results from our study compare favorably with those from observational studies of lateral approaches to interbody fusion in the treatment of degenerative lumbar spinal stenosis and spondylolisthesis. In a retrospective analysis of 15 patients who underwent minimally invasive lateral transpsoas lumbar interbody fusion (XLIF) at 20 levels, Elowitz et al[12] also found radiologic evidence of central canal decompression, evidenced by increases in the dural sac diameter of +0.38 cm in the anteroposterior axis and +0.45 cm in the transverse axis. The mean anteroposterior dural sac/osseous spinal canal ratio improved from 52.6% to 72.1%, and the same ratio in the transverse axis from 51.0% to 69.2%.

In a prospective nonrandomized clinical study on the indirect decompressive effects of the XLIF procedure performed in 21 patients at 43 operative levels, Oliveira et al[29] showed substantial dimensional improvements in radiologic parameters of disk height, neural foraminal height, foraminal area, and central canal diameter. Importantly, they report an increase in midsagittal anteroposterior central canal diameter from 0.71 to 0.95 cm, corresponding to postoperative increases of 33.1% in midsagittal central canal diameter and 8.4% in axial central canal area. Foraminal decompression was significant, with mean increases of +0.30 cm (41.9%) in disk height, +0.28 cm (13.5%) in neural foraminal height, and +0.60 cm^2 (24.7%) in neural foraminal area.

Comparatively, the MIS-TLIF approach may provide similar or even greater central canal decompression than XLIF. In a prospective multicenter study by Isaacs et al,[30] the postoperative mean changes in midsagittal anteroposterior central canal diameter (+0.25 vs. +0.1 cm) and axial central canal area (+0.431 vs. +0.041 cm^2) were greater in the MIS-TLIF compared with the XLIF group. However, the magnitude of changes in each segmental lordosis, disk height, and neural foraminal height were greater in the XLIF group.

In the above and other studies,[10–12,29] the authors reason that lateral access to the lumbar spine is ligament-sparing and allows for aggressive disk removal with placement of a large intrinsically stable construct across the interspace. This process not only assures a proper graft bed for fusion, but also enables central canal decompression and interbody distraction that restores disk height and neural foraminal height, without the need for direct resection of posterior elements and its associated morbidities.

Findings in Context: Anterior Access Lumbar Interbody Fusion (ALIF)

Central and neural foraminal decompression can also be achieved using ALIF. In a prospective observational analysis of computed tomography scans in 140 patients who underwent ALIF at 184 levels, Rao et al[8] reported significant

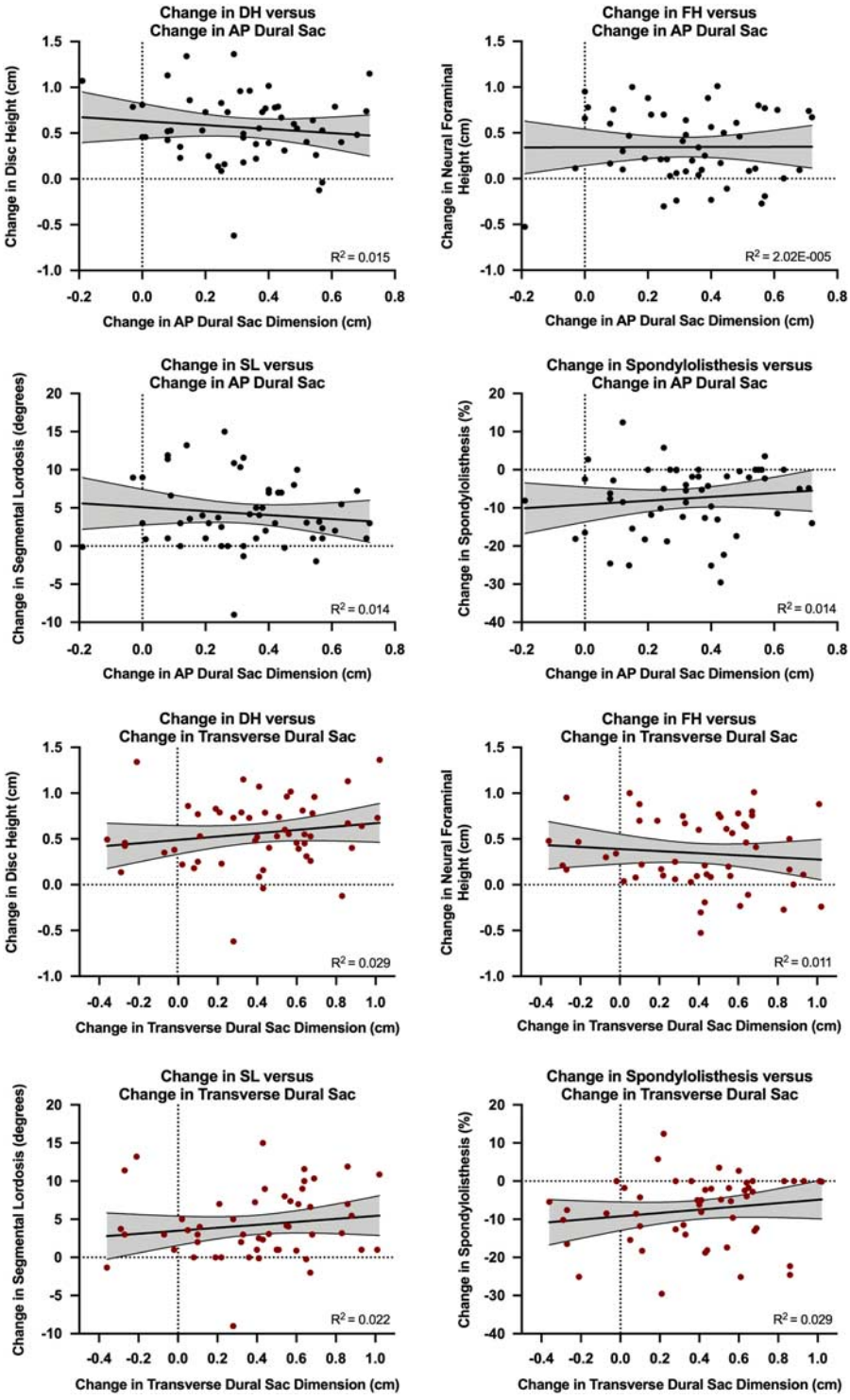

FIGURE 4. Scatterplots of changes in lumbar sagittal segmental parameters relative to changes in anteroposterior and transverse dural sac dimensions. Data are presented for "all patients." AP indicates anteroposterior; DH, disk height; FH, neural foraminal height; SL, segmental lordosis. full color online

dimensional increases of +0.37 cm (77%) in disk height, +0.3 cm (21%) in neural foraminal height, and +0.6 cm^2 (66.7%) in neural foraminal area. In the setting of grade II or higher spondylolisthesis, Xu et al[31] report that MIS ALIF and XLIF achieve high rates of complete reduction of the spondylolisthesis (ALIF 87.5%, XLIF 75.0%), significant increases in segmental lordosis (ALIF 15.0 degrees, XLIF 5.6 degrees), and clinically meaningful improvements in

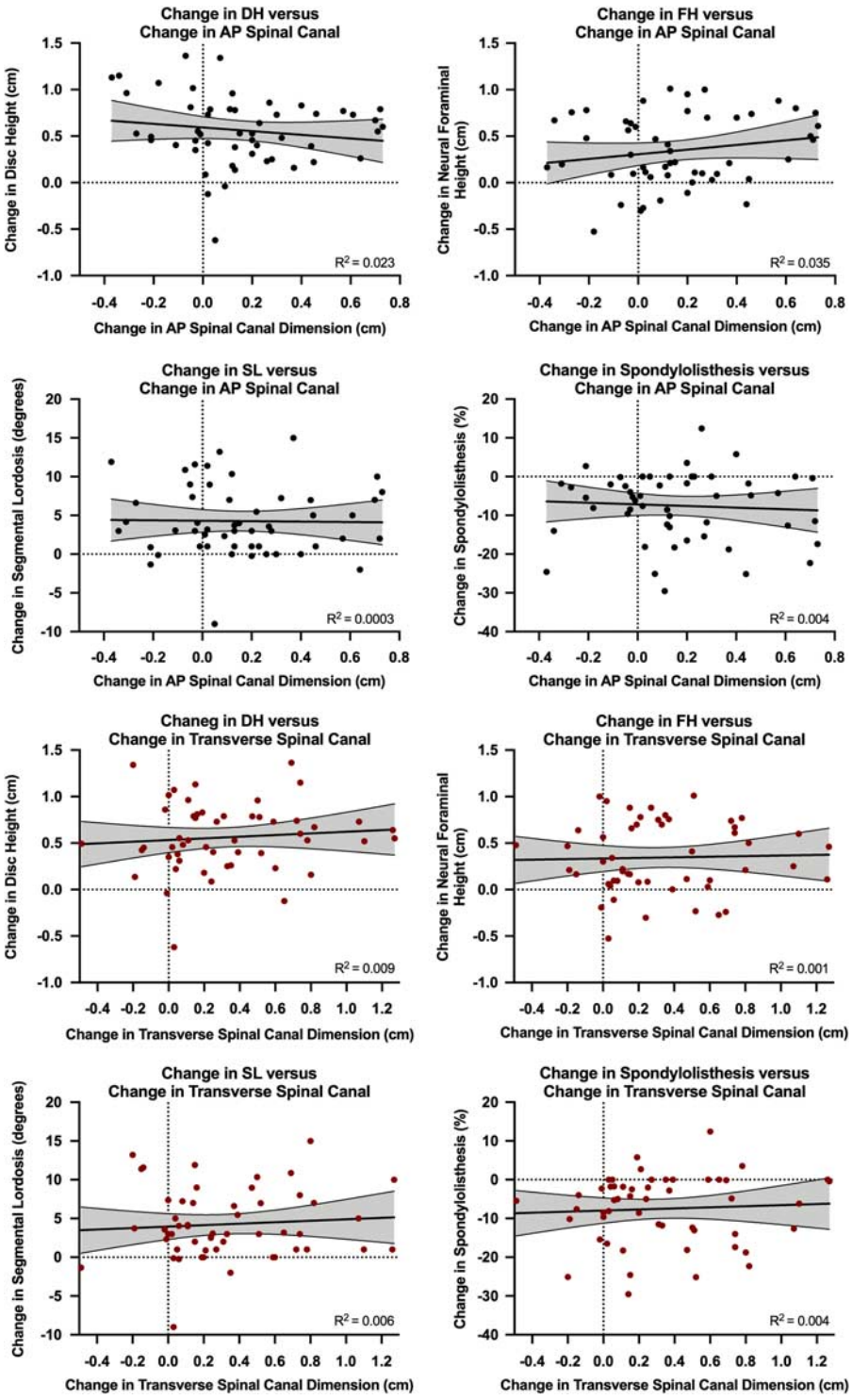

FIGURE 5. Scatterplots of changes in lumbar sagittal segmental parameters relative to changes in anteroposterior and transverse osseous spinal canal dimensions. Data are presented for "all patients." AP indicates anteroposterior; DH, disk height; FH, neural foraminal height; SL, segmental lordosis. full color online

patient-reported outcomes of pain and physical function. In their series, no patient required subsequent posterior decompression due to inadequate relief of radiculopathy or neurogenic claudication. Thus, symptomatic patients may benefit from the indirect decompression achieved by reduction of a high-grade spondylolisthesis and restoration of disk height, which translates to additional gains in neural foraminal height and central canal diameter.

Direct and Indirect Mechanisms of Lumbar Spinal Decompression

Lumbar spinal stenosis is a common and progressive degenerative process that arises due to a combination of multiple factors—thickening of the ligamentum flavum, hypertrophy of the facet joint capsules, osteophyte formation, disk bulge or herniation, and dynamic spondylolisthesis with narrowing of the neural foramina and central canal. Direct decompression of symptomatic neural elements is achieved via the resection of impinging bone, ligaments, and disk material for placement of an interbody device. Increasingly, a mechanism for indirect decompression is cited to explain radiologic and clinical improvements following lumbar interbody fusion. We have previously shown that in the case of MIS-TLIF, the placement of a structural interbody device graft, reduction of the spondylolisthesis, and instrumented interbody fixation/fusion provides important *neural foraminal* decompression.[19,20,32] This is likely facilitated by the restoration of disk height, segmental lordosis, segmental realignment, unbuckling and stretch of the ligamentum flavum and annular fibers, and elimination of dynamic posture-related stenosis.

The presumed mechanism for indirect foraminal decompression following ALIF and lateral approaches to lumbar interbody fusion has been extrapolated to the central spinal canal. We sought to evaluate whether this is also observed in the posterolateral MIS-TLIF. In the current analysis, we found significant central spinal canal decompression after surgery, which had absent or weak associations with changes in disk height, segmental lordosis, or reduction of spondylolisthesis. Our data do not support a mechanism of central canal decompression achieved primarily via indirect means. Rather, we suspect a mechanism of central canal decompression that is driven by a combination of direct and indirect techniques, likely with important contributions from the former; namely the discectomy, facetectomy, and laminotomy.

Indeed, analyses of radiologic changes following ALIF and lateral lumbar interbody fusions support this mechanism of primary direct central canal decompression. In a retrospective review of 33 patients with central canal stenosis who had undergone ALIF with percutaneous pedicle screw fixation, Kim et al[9] observed significant widening of mean dural sac cross-sectional area from 0.61 to 0.99 cm^2, and increases in anteroposterior diameter from 0.53 to 0.82 cm. The mean expansion ratio (postoperative cross-sectional area/preoperative cross-sectional area) was 1.36, which showed no correlation with disk height change ($r = 0.137$) or reduction rate of listhesis ($r = 0.127$). Similarly, in a prospective study of 28 consecutive patients with degenerative lumbar stenosis who underwent oblique lateral interbody fusion combined with percutaneous pedicle screw fixation at 52 lumbar levels, Fujibayashi et al[10] reported a mean increase in dural sac cross-sectional area from 0.996 cm^2 preoperatively to 1.343 cm^2 postoperatively. The were no significant associations between the change in dural sac cross-sectional area and the changes in disk height, segmental lordosis, and patient-reported outcome measures. Thus, the contributions of indirect decompression techniques on the central spinal canal after lumbar interbody fusion are possibly overstated.

Lastly, central canal decompression via indirect effects is perhaps more of an important consideration for MISS anterior or lateral approaches, as it obviates the need for direct posterior decompression requiring a separate incision and approach. This is not the case for MIS-TLIF, whereby additional posterior central decompression is easily achieved by aiming the tubular retractor medially and extending the extent of bony resection.[21]

Limitations

Our study has several important limitations. First, this is a retrospective study with a relatively small sample size and variable follow-up. Second, the radiologic results are subject to measurement bias in favor of decompressive effects. In this case, blinding the data collector to operative status during measurements of central canal dimensions is not possible, as a patient's postoperative status with relation to the MIS-TLIF intervention is obvious by looking at the instrumentation on MRI scans or radiographs. Third, we acknowledge the potential for selection bias in our patient sample, as it is not our routine practice to obtain an MRI scan of the lumbar spine in a clinically improving or otherwise asymptomatic patient postoperatively. Thus, the interpretation and external validity of the results from our patient cohort must be considered with caution, especially when generalized to the typical postoperative MIS-TLIF patient. Fourth, the contribution of direct decompression techniques on central canal decompression could not be evaluated, as we were not able to quantify the extent of removal of disk material, ligaments, facets, and laminae. Last, the clinical effects of neural decompression following MIS-TLIF could not be investigated, as we did not perform assessments of walking distance, evaluations of leg symptoms ipsilateral and contralateral to the side of surgery, nor patient-reported outcome measures for general health and lumbar disease-specific pathology.

CONCLUSIONS

Patients with degenerative lumbar spondylotic disease and concurrent moderate to severe spinal stenosis who underwent MIS-TLIF with placement of either a static or an expandable interbody device experienced radiologic improvements in dural sac dimensions, osseous spinal canal dimensions, and radiographic sagittal segmental parameters of disk height, neural foraminal height, segmental lordosis, and spondylolisthesis. There were no meaningful associations between the changes in dural sac dimensions nor osseous spinal canal dimensions relative to the corresponding changes in each of the sagittal lumbar segmental parameters. The data *do not* provide evidence for a mechanism of central canal decompression achieved primarily via indirect means. Rather, they are suggestive of a mechanism of lumbar central spinal canal decompression that is driven by a combination of direct and indirect techniques.

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