North American Spine Society Journal (NASSJ) 10 (2022) 100110

Contents lists available at ScienceDirect

North American Spine Society Journal (NASSJ)

journal homepage: www.elsevier.com/locate/xnsj

Clinical Studies

Radiographic analysis of neuroforaminal and central canal decompression following lateral lumbar interbody fusion☆

Bryan Zheng*, Owen P. Leary, David D. Liu, Sarah Nuss, Adriel Barrios-Anderson, Spencer Darveau, Sohail Syed, Ziya L. Gokaslan, Albert E. Telfeian, Jared S. Fridley, Adetokunbo A. Oyelese

Department of Neurosurgery, Warren Alpert Medical School of Brown University, Providence, RI 02906, United States

A R T I C L E I N F O

Keywords:
Lateral lumbar interbody fusion
Minimally invasive surgery
Degenerative lumbar stenosis
Magnetic resonance imaging
Facet joint osteoarthritis

A B S T R A C T

Background: Lateral lumbar interbody fusion (LLIF) is a minimally invasive surgical option for treating symptomatic degenerative lumbar spinal stenosis (DLSS) in select patients. However, the efficacy of LLIF for indirectly decompressing the lumbar spine in DLSS, as well as the best radiographic metrics for evaluating such changes, are incompletely understood.

Methods: A single-institutional cohort of patients who underwent LLIF for DLSS between 5/2015 – 12/2019 was retrospectively reviewed. Diameter, area, and stenosis grades were measured for the central canal (CC) and neural foramina (NF) at each LLIF level based on preoperative and postoperative T2-weighted MRI. Baseline facet joint (FJ) space, degree of FJ osteoarthritis, presence of spondylolisthesis, interbody graft position, and posterior disc height were analyzed as potential predictors of radiographic outcomes. Changes to all metrics after LLIF were analyzed and compared across lumbar levels. Preoperative and intraoperative predictors of decompression were then assessed using multivariate linear regression.

Results: A total of 102 patients comprising 153 fused levels were analyzed. Pairwise linear regression of stenosis grade to diameter and area revealed significant correlations for both the CC and NF. All metrics except CC area were significantly improved after LLIF ($p < 0.05$, 2-tailed t-test). Worse FJ osteoarthritis ipsilateral to the surgical approach was predictive of greater post-operative CC and NF stenosis grade ($p < 0.05$, univariate and multivariate ordinary least squares linear regression). Lumbar levels L3-5 had significantly higher absolute postoperative CC stenosis grades while relative change in CC stenosis at the L2-3 was significantly greater than other lumbar levels ($p < 0.05$, one-way ANOVA). There were no baseline or postoperative differences in NF stenosis grade across lumbar levels.

Conclusions: Radiographically, LLIF is effective at indirect compression of the CC and NF at all lumbar levels, though worse FJ osteoarthritis predicted higher degrees of post-operative stenosis.

Introduction

Lateral lumbar interbody fusion (LLIF) is a minimally invasive surgical option in select individuals with an indication for lumbar fusion (L1-5) or those with degenerative disc disease associated stenosis that is not amenable to direct posterior decompression. Originally introduced as an alternative approach for anterior lumbar interbody fusion by Ozgur et al. in 2006, LLIF has since become a popular means of minimally invasive indirect decompression of the central canal (CC) and neural foramina (NF) in degenerative lumbar spinal stenosis (DLSS) [1]. While not without limitations, LLIF tends to be associated with fewer and milder complications as well as shorter hospitalization compared to posterior approaches [2–7]. Studies evaluating the ability of LLIF to significantly decompress the central canal have demonstrated mixed results, in part due to the multiple radiographic metrics utilized to evaluate radiographic improvement [8].

Multiple numerical metrics have been studied to quantify the degree of lumbar degenerative changes, primarily using lumbar spine MRI, including anterior-posterior CC diameter, dural sac area, and cranio-caudal neuroforaminal diameter [8–12]. Most radiologists use qualitative categorization of both CC and NF stenosis using clinically accepted terminology, such as “mild”, “moderate”, and “severe.” In order to reduce inter-user variability in stenosis grading, GY Lee et al. developed a system for assigning grade I (mild), grade II (moderate), and grade

☆ Note: This paper has not been previously presented or published in any form.

* Corresponding author at: Department of Neurosurgery, Rhode Island Hospital, APC Building, 6th Floor, 593 Eddy St, Providence, RI 02903, United States.
E-mail address: bryan_zheng@brown.edu (B. Zheng).

https://doi.org/10.1016/j.xnsj.2022.100110
Received 7 February 2022; Accepted 28 February 2022
Available online 6 March 2022

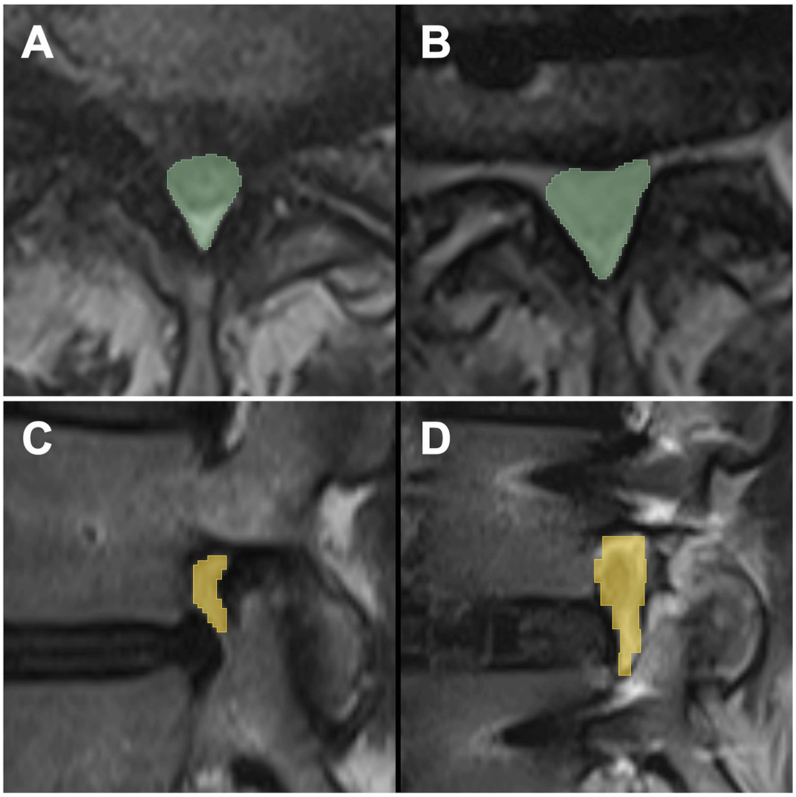

Fig. 1. Representative contours of the CC and NF on T2-weighted MRI used for area measurements. (A) Sample contour of the CC at mid disc level in the axial plane pre-LLIF demonstrating moderate (grade II) stenosis. **(B)** Post-operative CC contour demonstrating increased area with no stenosis (grade 0). **(C)** Pre-LLIF contour of (right) NF with severe (grade III) stenosis on sagittal view. **(D)** Contour of the same NF with improved area and stenosis (grade I) after decompression.

III (severe) canal stenosis in the lumbar spine based on amount of cerebrospinal fluid (CSF) seen around and between the nerves of the cauda equina [13]. Analogous criteria applied to the NF were defined by S Lee et al. based on extent of perineural fat effacement or direct encroachment of structures surrounding the exiting nerve root [14]. Although these validated grading methods are a convenient and efficient way to communicate radiographic findings, they have not yet been widely adopted clinically, nor have their correlations with geometric measurements been evaluated in the context of surgery for DLSS.

In this study of LLIF patients from a single center, we sought to quantify the radiographic efficacy of LLIF for indirect decompression as evaluated by CC and NF diameter, area, and stenosis grade. Leveraging our comparative analysis of these metrics, we then tested the hypothesis that baseline radiographic features are associated with better or worse radiographic outcomes following LLIF.

Methods

Selection of study population

The electronic medical records (EMR) of all patients who underwent single-level or multi-level LLIF for DLSS between May 2015 and December 2019 at a single academic medical center with one of four spine surgeons were retrospectively reviewed. Preoperative, intraoperative, and all available radiographic data were extracted for analysis.

Patients who had prior or concurrent posterior decompression at the index levels that confound the assessment of indirect decompression achieved with LLIF (e.g., laminectomy, laminotomy, foraminotomy) were excluded. Patients whose pathologies could be reasonably addressed by direct posterior decompression without fusion were also excluded. As such, patients included in this study had indications for lumbar fusion separate from decompression including instability, adjacent-level disease, severe degenerative disc/facet disease with axial back pain and instability, or severe bilateral NF stenosis for which aggressive decompression would have introduced iatrogenic instability.

This study includes only patients for whom preoperative and postoperative T2-weighted MRI were available. To assess the adequacy of decompression, postoperative MRI scans were ordered in some cases prior to staged supplemental instrumentation or prior to discharge from the hospital, while others were ordered later during clinical follow-up. Notably, many patients had postoperative lumbar spine radiographs and CT scans available either in addition to or in leiu of MRI, however measurements were only performed on MRIs in order to clearly discern soft tissue details for stenosis grading according to previously validated grading systems [13–15].

Evaluation of radiographic features

Diameters and disc heights were measured directly in the EMR's picture archiving and communication system (PACS). CC and NF cross-sectional areas were calculated by contouring the respective regions in a free, open-source image segmentation software (Fig. 1, *3D Slicer Project v4.10.2, The Brigham and Women's Hospital, Inc.*). At each index level, diameters encompassed the anterior-posterior extent of the CC and the inter-pedicle height for the NF. Disc height was defined as the intervertebral distance at the posterior vertebral border in the mid-sagittal plane. For area measurements, regions of hyperintense signal were taken to represent relevant regions including perineural or epidural fat. Stenosis grades for the CC and NF were determined based on previously validated grading systems by GY Lee (Fig. 2) and S Lee (Fig. 3) [13,14]. Changes in each metric were assessed between the last available preoperative MRI and first postoperative MRI to capture the most immediate effect of decompression achieved during the index LLIF procedure. Post-LLIF diameters and areas were compared to the preoperative values on a relative scale as ratios, while the absolute difference of stenosis grades was analyzed.

For evaluation of FJ osteoarthritis as a potential predictor of poor decompression, we utilized an existing methodology which Weishaupt et al. adapted from Pathria et al. for grading facet joint (FJ) osteoarthritis on MRI [15,16]. Preoperative disc height at index LLIF levels was

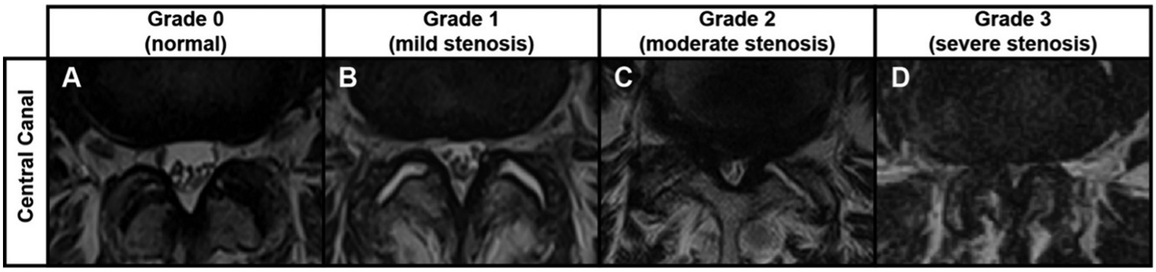

Fig. 2. Instances of each stenosis grade for the central canal (CC) based on GY Lee et al. (A) Grade 0 (normal) CC stenosis with no obliteration of cerebrospinal fluid (CSF). **(B)** Grade I (mild) CC stenosis with obliteration of cerebrospinal fluid (CSF) but clear separation of the cauda equina. **(C)** Grade II (moderate) CC stenosis with significant obliteration of cerebrospinal fluid (CSF) and partial aggregation of the cauda equina. **(D)** Grade III (severe) CC stenosis with complete obliteration of cerebrospinal fluid (CSF); rootlets of cauda equina are not distinguishable.

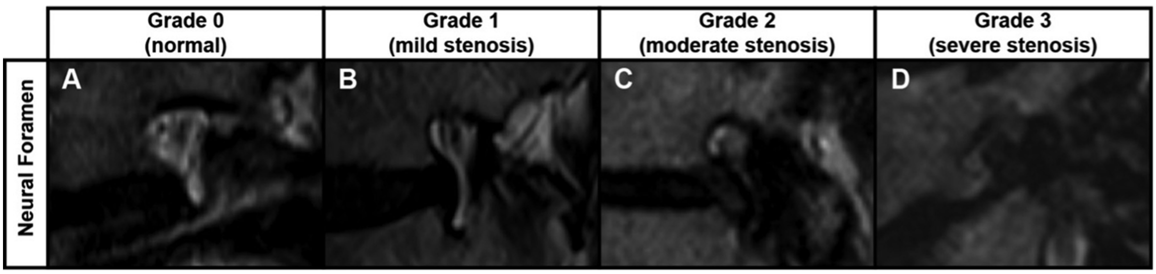

Fig. 3. Instances of each stenosis grade for neural foramen (NF) based on S Lee et al. (A) Grade 0 (normal) NF stenosis with no effacement of perineural fat. **(B)** Grade 1 (mild) NF stenosis with effacement of perineural fat in the cranio-caudal direction (effacement of perineural fat in the anterior-posterior direction would also qualify for this grade). **(C)** Grade 2 (moderate) NF stenosis with near complete effacement of perineural fat in all directions but no morphologic change of the nerve root. **(D)** Grade 3 (severe) NF stenosis with compression and morphologic change of the nerve root.

assessed in the midsagittal plane at the posterior edge of the disc space. Graft position was evaluated postoperatively as "posterior," "middle," or "anterior" based on dividing the disc space into thirds and determining the region in which the majority of the graft was present. Spondylolisthesis at each index level was graded using the Meyerding classification system, though analysis was conducted in a binary fashion since all instances were Grade I except for one incidence of Grade II [17].

Statistical analysis

Simple ordinary least squares linear regression was used to assess for correlation between different metrics of the same anatomical structure of interest (i.e., CC and NF). Two-tailed *t*-tests confirmed whether or not a radiographic metric changed significantly after LLIF. Correlation between predictive features and postoperative stenosis grade was assessed using univariate and multivariate ordinary least squares linear regression. Analysis of variances (ANOVA) was used to assess differences in metrics across individual lumbar levels. Statistics were performed Python (*Python Software Foundation, v3.6.8*) with statistical significance defined as $p < 0.05$ with Benjamini-Hochberg correction procedures for multiple comparisons, applying a false discovery rate of 0.05.

This study was approved by the local Institutional Review Board (#816619). All patient data obtained were de-identified for analysis.

Results

A total of 102 subjects with 153 fused levels were analyzed, averaging 1.5 index levels per patient. Patients had a mean age of 66 years (range 29–86). Most index levels were in the lower lumbar spine, with 7 at L1-2, 35 at L2-3, 57 at L3-4, and 53 at L4-5. Baseline characteristics are summarized in Table 1. First, categorical stenosis grades were shown to be suitable metrics for evaluating radiographic changes. There were significant correlations of different degrees between diameters, areas, and stenosis grade that described the same anatomical structure (i.e., CC and NF), both pre- and post-operatively (all $p < 0.001$). Pairwise Pearson correlation coefficients with 95% confidence intervals are compiled in Table 2. Stenosis grade of both the CC and NF were weak correlates of diameter (CC: r = -0.278 [-0.419, -0.125], p = 0.0005, NF: r = -0.280 [-0.382, -0.173], $p < 0.0001$) and moderate correlates of area (CC: r = -0.513 [-0.641, -0.357], $p < 0.0001$, NF: r = -0.531 [-0.608, -0.444], $p << 0.0001$), despite being significantly easier and less laborious to obtain.

Table 1
Characteristics of N = 102 subjects included.

Age (years)	66 (28 – 85)
Sex (female: male)	54: 48
Surgical Approach (left: right)	81: 21
Levels Fused	153
1	67
2	22
3	10
4	3
Index Levels	
L1-2	7
L2-3	35
L3-4	57
L4-5	53
Pre-op MRI (days before LLIF)	140 (3 – 765)
Post-op MRI (days after LLIF)	88 (0 – 818)
Time Between MRIs (days)	251 (4 – 1093)

Notably, all metrics of the CC and bilateral NF, except for CC area, were significantly improved after LLIF (Fig. 4). However, the magnitude of changes in CC and NF diameter, in particular, were relatively small whereas the mean improvements in both CC and NF stenosis manifested as approximately half-point decreases in grade. Note that reductions in grade indicate improvement in stenosis (higher grade indicates more stenosis), while increases in area and diameter indicate improvement. On average, posterior disc height increased by a factor of 2.04 +/- 1.425. As expected, FJ osteoarthritis grade did not change significantly follow-

Table 2
Correlation between canal and neuroforaminal measurements (with mean values and standard deviations).

	Canal Diameter1.39 ± 0.388 cm	Canal Area131.3 ± 69.66 mm^2
Canal Stenosis Grade1.95 ± 1.120	r = -0.278 [-0.419, -0.125]p = 0.0005	r = -0.513[-0.641, -0.357]p < *0.0001*
Canal Area	r = 0.429 [0.260, 0.573]p < *0.0001*	
	Foraminal Diameter2.01 ± 0.343 cm	**Foraminal Area**71.7 ± 33.28 mm^2
Foraminal Stenosis Grade1.55 ± 1.028	r = -0.280 [-0.382, -0.173]p < *0.0001*	r = -0.531 [-0.608, -0.444]p < *0.0001*
Foraminal Area	r = 0.340 [0.236, 0.437]p < *0.0001*	

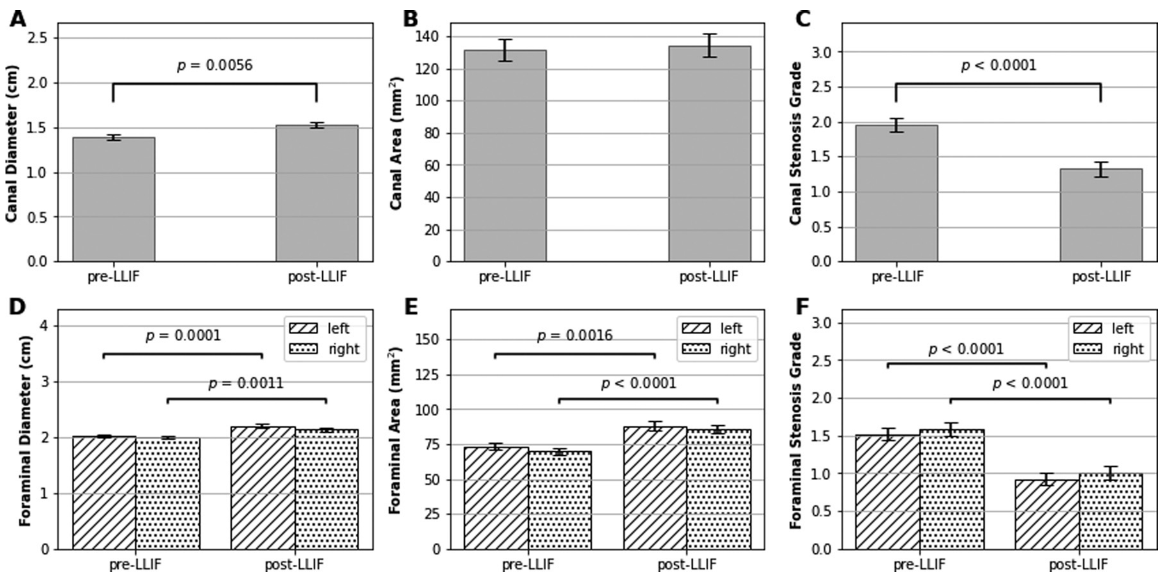

Fig. 4. Changes in radiographic metrics of lumbar anatomy after LLIF. (A) Anterior-posterior diameter (**A**) increased significantly following LLIF, though (**B**) area without a significant increase in area. (**C**) Canal stenosis grade, which is significantly correlated with both metrics, was significantly reduced (i.e., improved) as a result of LLIF. (**D-F**) All metrics of the NF bilaterally were improved significantly post-LLIF. (p-values represent results of a 2-tailed t-test for differences in means; alpha = 0.05)

Table 3
Predictors of pre-LLIF and post-LLIF central canal and neuroforaminal stenosis grade on *univariate* linear regression

	Univariate – r [95% CI]							
	Pre-LLIF				Post-LLIF			
	CC StenosisGrade		*NF StenosisGrade*		*CC StenosisGrade*		*NF Stenosis Grade*	
Age	***0.277[0.124, 0.417]***	***p* = 0.002**	0.199[0.041, 0.346]	***p* = 0.018**	***0.248[0.056, 0.422]***	***p = 0.018***	0.205[0.014, 0.381]	***p = 0.036***
Gender	-0.078[0.124, 0.417]	p = 0.648	-0.080[-0.236, 0.080]	p = 0.648	0.068[-0.129, 0.259]	p = 0.648	0.045[-0.148, 0.235]	p = 0.648
Number of Fused Levels	0.015[-0.144, 0.173]	p = 0.859	***0.265[0.111, 0.407]***	***p = 0.004***	-0.167[-0.350, 0.029]	p = 0.189	0.054[-0.139, 0.243]	p = 0.777
Graft PlacementA: 38, M: 60, P: 8	-0.133[-0.316, 0.059]	p = 0.629	-0.071[-0.258, 0.122]	p = 0.629	-0.037[-0.231, 0.159]	p = 0.710	-0.092[-0.280, 0.102]	p = 0.629
Spondylolisthesis *Any*N = 46	0.033[-0.126, 0.191]	p = 0.932	-0.031[-0.188, 0.129]	p = 0.932	0.253[0.062, 0.427]	***p = 0.041***	0.008[-0.184, 0.200]	p = 0.932
*Antero*N = 34	0.064[-0.095, 0.221]	p = 0.765	0.003[-0.155, 0.162]	p = 0.966	0.224 [0.031, 0.401]	p = 0.094	-0.055[-0.245, 0.138]	p = 0.765
*Retro*N = 12	0.034[-0.126, 0.191]	p = 0.679	0.066[-0.094, 0.222]	p = 0.561	-0.152[-0.336, 0.044]	p = 0.514	-0.105[-0.290, 0.089]	p = 0.561
Facet JointOsteoarthritis Grade	0.063[-0.098, 0.221]	p = 0.444	***0.220[0.062, 0.367]***	***p = 0.010***	***0.319[0.132, 0.484]***	***p = 0.005***	***0.261[0.072, 0.432]***	***p = 0.010***
Posterior Disk Height	-0.145[-0.297, 0.014]	p = 0.124	-0.136[-0.289, 0.023]	p = 0.124	0.178[-0.017, 0.360]	p = 0.124	0.061[-0.132, 0.250]	p = 0.534

ing LLIF (Left: 1.08 +/- 0.049 vs 1.12 +/- 0.057, p = 0.60; Right: 1.08 +/- 0.049 vs 1.00 +/- 0.057, p = 0.29).

Consequently, CC and NF stenosis grades were selected as the radiographic outcome metrics of choice for our predictive analysis since they are substantially more efficient to obtain than diameters, and particularly areas. Both CC and NF were found to be correlated with area as well as diameter to a lesser degree. Pearson's correlation coefficients between demographic and commonly assessed radiographic features and degree of pre- and post-operative CC and NF stenosis are tabulated in Table 3 (univariate) and Table 4 (multivariate). With respect to the distribution of FJ osteoarthritis grades, there were 18 levels with Grade 0 (no arthropathy), 102 levels with Grade 1 (mild), 26 levels with Grade 2 (moderate), and 4 levels with Grade 3 (severe) osteoarthritis. Mean baseline posterior disc height was 0.47 +/- 0.015 cm. Preoperative correlations are included to determine if post-operative outcomes reflect baseline relationships or if significant covariates are truly predictive.

On multivariate linear regression, pre-LLIF CC stenosis grade was only positively correlated with age (r = 0.277 [0.124, 0.417], p = 0.002), while pre-LLIF NF stenosis grade was only correlated with number of levels fused (r = 0.265 [0.111, 0.407], p = 0.017) and FJ osteoarthritis grade (r = 0.220 [0.062, 0.367], p = 0.008). More severe preoperative FJ osteoarthritis grade was significantly correlated with worse postoperative CC (r = 0.319 [0.132, 0.484], p = 0.030) and NF (r = 0.261 [0.072, 0.432], p = 0.003) stenosis grades on multivariate linear regression. While the relationship between postoperative NF stenosis and preoperative FJ osteoarthritis grade could be accounted for by the corresponding association with preoperative NF stenosis, the same was not true for CC stenosis, suggesting that high-grade FJ osteoarthritis may independently limit the success of LLIF at indirect CC decompression at

Table 4
Predictors of pre-LLIF and post-LLIF central canal and neuroforaminal stenosis grade on *multivariate* linear regression.

		Multivariate			
		Pre-LLIF		Post-LLIF	
		CC Stenosis Grade	*NF Stenosis Grade*	*CC Stenosis Grade*	*NF Stenosis Grade*
Age		***p = 0.002***	$p = 0.677$	***p = 0.039***	$p = 0.192$
Gender		$p = 0.934$	$p = 0.786$	$p = 0.888$	$p = 0.687$
Number of Fused Levels		$p = 0.314$	***p = 0.017***	$p = 0.126$	$p = 0.796$
Graft Placement		$p = 0.553$	$p = 0.654$	$p = 0.661$	$p = 0.373$
Spondylolisthesis	*Any*	$p = 0.415$	$p = 0.853$	$p = 0.212$	$p = 0.648$
	Antero	$p = 0.775$	$p = 0.888$	$p = 0.840$	***p = 0.046***
	Retro	$p = 0.858$	$p = 0.983$	$p = 0.425$	$p = 0.159$
Facet Joint Osteoarthritis Grade		$p = 0.591$	***p = 0.008***	***p = 0.030***	***p = 0.003***
Posterior Disk Height		$p = 0.098$	$p = 0.294$	$p = 0.428$	$p = 0.578$

affected levels. Older age was also correlated with worse postoperative CC stenosis grade ($r = 0.248$ [0.056, 0.422], $p = 0.039$) and, on univariate analysis only, worse postoperative NF stenosis grade ($r = 0.205$, [0.014, 0.381], $p = 0.036$). The presence of spondylolisthesis was also associated with worse postoperative CC stenosis grade on univariate but not multivariate analysis ($r = 0.253$ [0.062, 0.427], $p = 0.041$). When cases of anterolisthesis versus retrolisthesis were analyzed separately, the relationship was found to primarily be driven by cases of anterolisthesis ($r = 0.224$ [0.031, 0.401], $p = 0.094$) rather than retrolisthesis ($r = -0.152$ [-0.336, 0.044]; $p = 0.514$).

Differences in preoperative, postoperative, and relative changes in CC and NF stenosis grade across lumbar levels are compiled in Fig. 5. There were no differences across levels in terms of CC stenosis grade or NF stenosis grade pre-LLIF, however lower lumbar levels (L3-5) had significantly less improvement in CC stenosis grades than upper lumbar levels (L1-3), suggesting a somewhat lower tendency to benefit from indirect CC decompression according to this metric assessed postoperatively ($p = 0.016$). On average, the L2-3 level had the single greatest improvement in CC stenosis grade from pre- to post-LLIF of any level, improving by an average of 1.5 points. Statistically, upper and lower lumbar levels appeared to benefit equally from indirect neuroforaminal decompression by LLIF in terms of changes in NF stenosis grade. Lastly, mean baseline FJ osteoarthritis grades increased moving caudally down the lumbar spine, though this trend did not reach statistical significance (L1-2: 0.86 +/- 0.261, L2-3: 1.00 +/- 0.082, L3-4: 1.14 +/- 0.081, L4-5: 1.18 +/- 0.100; $p = 0.106$, ordinary least squares linear regression).

While most patients reliably received preoperative MRIs with T2-weighted sequences in a relatively uniform interval prior to surgery, the duration between LLIF and the first available postoperative MRI was variable and dependent on provider preference. Immediate postoperative MRI scans were typically performed for radiographic assessment of central canal decompression often in asymptomatic patients undergoing staged posterior stabilization while those obtained in delayed fashion were more likely to be performed as part of ongoing assessment of residual or recurrent postoperative clinical symptoms. As it is possible this range of follow-up times influenced the results presented, all analyses were repeated under more standardized inclusion criteria at mild cost to sample size. When only the cohort of patients whose preoperative and postoperative imaging was obtained within a year of the index procedure (N = 94), there was remarkably no impact on the discussed results. Metrics which changed significantly following LLIF (Fig. 4) remained significant, as did the significant differences in CC and NF stenosis across levels (Fig. 5), and facet joint osteoarthritis remained a significant covariate for postoperative CC and NF stenosis (Tables 3, 4).

Discussion

Compared to open posterior approaches, lateral transpsoas approaches to interbody fusion offer lower blood loss, fewer problems with wound healing, and reduced hospitalization time [2–7]. However, selecting the best metrics for evaluating decompression achieved with LLIF is important for objective evaluation of efficacy on imaging. To our knowledge, this is the first study to comprehensively compare categorical foraminal and central canal stenosis grading with diameter and area measurements to characterize radiographic efficacy of LLIF, and then utilize the best of these metrics to identify clinical predictors of successful decompression of the CC and NF in a sizable single-site cohort.

Grading the degree of CC and NF stenosis is typically performed qualitatively, or using accepted criteria based on perioperative MRI [13,14]. Alternatively, foraminal diameter or height and CC diameter assessed on either sagittal or axial MRI are commonly used, quantitative, 1D radiographic metrics for diagnosing DLSS and evaluating radiographic success of decompression [9,10]. While inter-rater variability of CC and NF area measurements is yet to be quantified, area has a clearer objective parametric definition than stenosis grade, although there has been previous controversy over whether measurements of specific components within the CC or NF (e.g. the dural sac vs the entire CC) are more sensitive to decompression [11]. Though anterior-posterior CC diameter is an easy measurement that can be made in most clinical imaging management systems, it offers questionable clinical value [12,18]. Similarly, one-dimensional (1D) assessment of the neural foramina is suspected to be insufficient in characterizing extent of nerve root compression, which can originate from several directions around the circumference of the NF [8]. In particular, NF diameter is often poorly defined as the craniocaudal, inter-pedicle distance and as such, may not sufficiently capture compression of the exiting nerve root from disc herniation and facet hypertrophy. Clinical translation of these 2D anatomic metrics into practice have been limited by the fact that their measurement remains somewhat labor-intensive, though we demonstrate in this study that their variance can be adequately accounted for by stenosis grades. Thus, categorical grading of canal and neuroforaminal stenosis according to two previously published schemas provided practical substitutes for more objective metrics such as area and should be more widely adopted to reduce subjectivity during clinical evaluation of lumbar stenosis.

Building on findings that CC and NF stenosis grades are reliable metrics for evaluating extent of indirect decompression after LLIF, we identified demographic and radiographic factors which predict better decompression of these spaces following LLIF. Our study suggests that preoperative FJ osteoarthritis at the operative levels is an important consideration with respect to surgical planning. FJ osteoarthritis would be expected to correlate with preoperative stenosis due to facet impingement into both the CC and NF, but our analysis suggests baseline FJ grade differences correlated with baseline NF, but not CC, stenosis grade. However, in our regression models, baseline degree of FJ osteoarthritis was also an independent predictor of poor post-LLIF decompression of both the CC and NF, as evaluated on both univariate and multivariate regression. Future studies should further investigate this relationship; it is possible reduced motion in the facet joint at index levels may im-

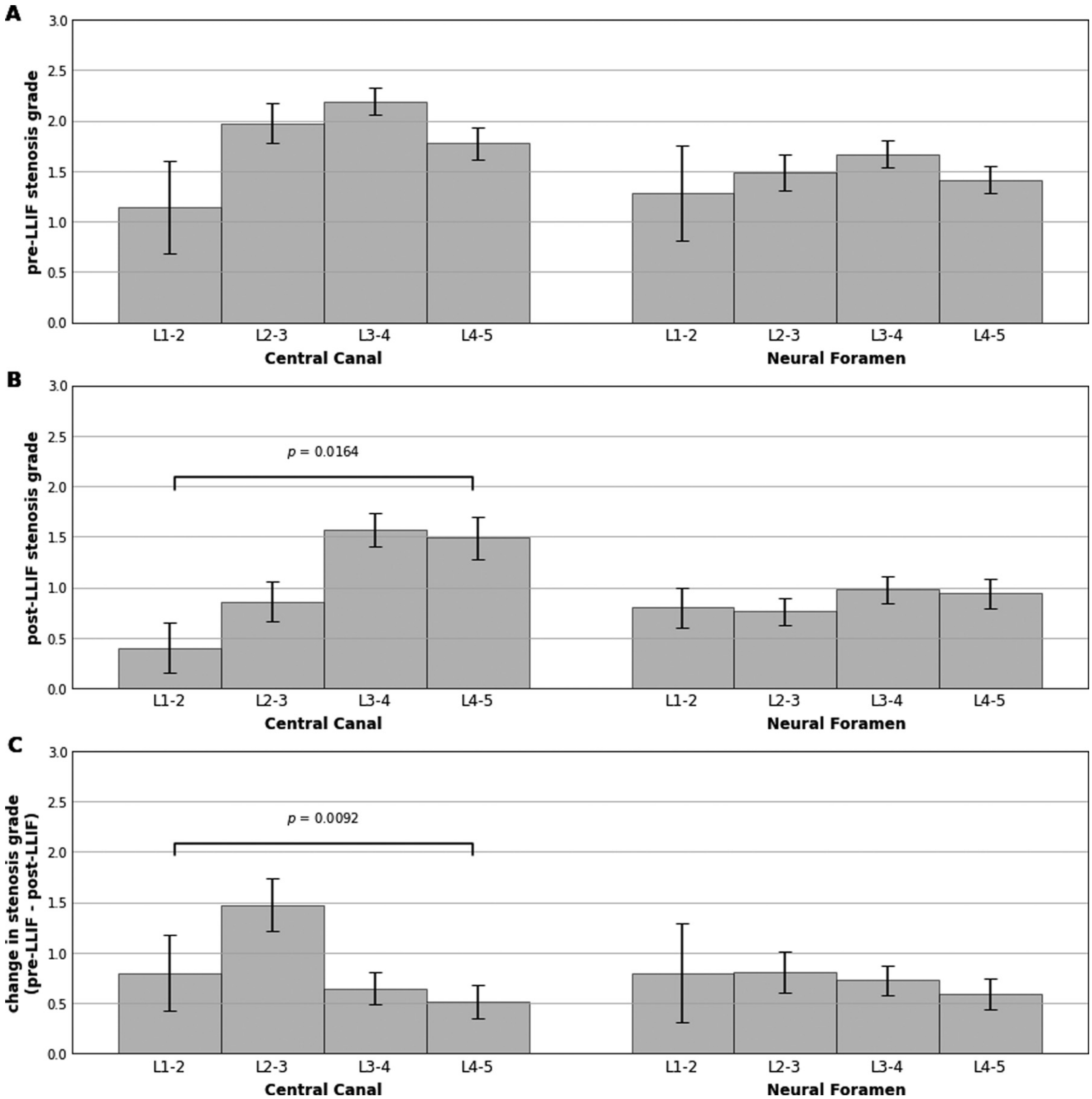

Fig. 5. Differences in baseline, post-LLIF, and relative changes in stenosis grades of the CC and NF. (A) There were no differences between lumbar levels for either the CC or NF. (**B**) Lower lumbar levels (L3-5) had worse baseline CC stenosis grades, though no such difference existed for the NF. (**C**) As a consequence of differences in CC decompression, improvement at the L2-3 level emerged as significantly greater than the rest of the lumbar spine. Change was defined as pre-LLIF score – post-LLIF score to obtain a positive value. (*p*-values represent results of a one-way ANOVA tests for differences across groups; alpha = 0.05)

pair the ability to achieve adequate indirect decompression through the lateral approach, possibly representing a relative contraindication to a lateral-only approach to interbody fusion.

Although LLIF can be performed at any lumbar level, many surgeons prefer the operation at mid-lumbar levels due to greater risk of neurovascular injury and unfavorable anatomy of the iliac crest at lower lumbar levels. Prior studies have found comparable rates of complication after LLIF for L4-5 decompression versus alternative procedures such as anterior lumbar interbody fusion (ALIF), with LLIF carrying lower risks of vascular and hypogastric plexus injury, yet higher probability of immediate but transient lumbar plexopathy [19–22]. Though multiple studies have individually analyzed changes in CC and NF area and/or diameter after LLIF with mixed results, few have focused on comparing these parameters across levels [23–25]. Kepler et al. found no statistically significant differences in decompression across levels as evaluated by change in foraminal area, which is corroborated by our findings [26]. However, we further extend these findings by demonstrating that LLIF is effective for indirect decompression, regardless of index level, in terms of all radiographic metrics assessed except for CC area (Fig. 4). We additionally show that upper lumbar levels (L1-2, L2-3) appeared to benefit even more relative to lower lumbar levels (L3-4, L4-5) in terms of indirect CC decompression. This trend appeared to be driven by the L2-3 level in particular, possibly due to ease of access. The data presented in this study contribute to the broader goal of choosing an approach for interbody fusion based on patient-specific considerations such as level of disease, underlying risk factors for specific complications, and CC vs. NF stenosis as the primary etiology of presenting symptoms.

Narrower CC and higher degree of interbody motion in the lower lumbar spine may render this region mechanically distinct [27–29]. The results of our analysis suggest that indirect decompression is not impacted by these typical anatomic and biomechanical differences between the upper versus lower lumbar spine, though upper lumbar levels appeared to appreciate statistically greater benefit. It should be additionally noted that spondylolisthesis at the lower lumbar levels, which can also be corrected by LLIF and notably contribute to canal stenosis more than at the upper lumbar levels, may contribute to some of the improved canal decompression observed at lower lumbar levels in this study. Indeed, there was a significant trend on univariate analysis towards improved post-LLIF canal stenosis grade in patients with spondylolisthesis, supporting prior literature that the LLIF approach may be helpful for addressing both loss of disc height and spondylolisthesis as contributors to degenerative stenosis. Many patients have overlapping degenerative pathologies, and the potential to address spondylolisthesis in the lower lumbar spine while indirectly decompressing the neuroforamina through a lateral approach only strengthens the perceived utility of LLIF for such cases.

While we identify several compelling correlations between radiographic features and successful indirect decompression following LLIF, an important future step would be further analysis of these metrics in terms of their ability to predict clinical outcomes. The precise relationship between LLIF-induced changes in lumbar anatomy and symptomatic relief in the setting of various degenerative foraminal and central stenosis etiologies are poorly understood [1,25]. Multiple prior studies have broadly examined the efficacy of LLIF in terms of symptomatic improvement of back and leg pain [1,9,10,26]. However, identifying radiographic predictors of non-improvement on either preoperative or immediate postoperative MRI may be clinically useful. Such analyses building upon the present results may contribute to better overall patient selection for lateral approaches based on likelihood of improvement, relative to specific nature of degenerative disease and presenting symptomatology, rather than based primarily or only upon the operative advantages of a particular approach, as is the current standard.

Limitations

As a retrospective study, there were no specific protocols employed for obtaining imaging data, resulting in heterogeneity in data availability and selection bias toward those who received postoperative MRIs. Additionally, comparisons between pre- and post-operative imaging are ideally made between the same axial and sagittal slices, which is difficult without highly precise image acquisition protocols. Clinical outcomes of LLIF were not considered in this radiographic study, largely owing to lack of quantitative symptom data in our retrospective dataset. Future analyses aiming to assess predictors of symptomatic improvement following LLIF would complement this radiological study and should adopt a prospective study design. Moreover, data obtained from a single institution also limits the generalizability of these results to non-academic centers with less LLIF experience.

Conclusions

Radiographically, LLIF is effective at indirect decompression of the neural foramina, and to a lesser extent the central canal. Using stenosis grades, worse baseline facet joint arthropathy predicts poor indirect decompression and may represent a relative contraindication for LLIF.

Funding disclosures

There were no sources of financial support for this study.

Declarations of Competing Interest

None.

References

[1] Ozgur BM, Aryan HE, Pimenta L, Taylor WR. Extreme lateral interbody fusion (XLIF): a novel surgical technique for anterior lumbar interbody fusion. Spine J 2006;6(4):435–43.
[2] Epstein NE. Review of risks and complications of extreme lateral interbody fusion (XLIF). Surg Neurol Int 2019;10:237.
[3] Rodgers WB, Gerber EJ, Patterson J. Intraoperative and early postoperative complications in extreme lateral interbody fusion: an analysis of 600 cases. Spine (Phila Pa 1976) 2011;36(1):26–32.
[4] Kwon B, Kim DH. Lateral lumbar interbody fusion: indications, outcomes, and complications. J Am Acad Orthop Surg 2016;24(2):96–105.
[5] Salzmann SN, Shue J, Hughes AP. Lateral lumbar interbody fusion-outcomes and complications. Curr Rev Musculoskelet Med 2017;10(4):539–46.
[6] Lehmen JA, Gerber EJ. MIS lateral spine surgery: a systematic literature review of complications, outcomes, and economics. Eur Spine J 2015;24(Suppl 3):287–313.
[7] Ohba T, Ebata S, Haro H. Comparison of serum markers for muscle damage, surgical blood loss, postoperative recovery, and surgical site pain after extreme lateral interbody fusion with percutaneous pedicle screws or traditional open posterior lumbar interbody fusion. BMC Musculoskelet Disord 2017;18(1):415.
[8] Lang G, Vicari M, Siller A, et al. Preoperative assessment of neural elements in lumbar spinal stenosis by upright magnetic resonance imaging: an implication for routine practice? Cureus 2018;10(4):e2440.
[9] Alimi M, Hofstetter CP, Cong GT, et al. Radiological and clinical outcomes following extreme lateral interbody fusion. J Neurosurg Spine 2014;20(6):623–35.
[10] Oliveira L, Marchi L, Coutinho E, Pimenta L. A radiographic assessment of the ability of the extreme lateral interbody fusion procedure to indirectly decompress the neural elements. Spine (Phila Pa 1976) 2010;35(26 Suppl):S331–7.
[11] Lim YS, Mun JU, Seo MS, et al. Dural sac area is a more sensitive parameter for evaluating lumbar spinal stenosis than spinal canal area: a retrospective study. Medicine (Baltimore) 2017;96(49):e9087.
[12] Hughes A, Makirov SK, Osadchiy V. Measuring spinal canal size in lumbar spinal stenosis: description of method and preliminary results. Int J Spine Surg 2015;9:3.
[13] Lee GY, Lee JW, Choi HS, Oh KJ, Kang HS. A new grading system of lumbar central canal stenosis on MRI: an easy and reliable method. Skeletal Radiol 2011;40(8):1033–9.
[14] Lee S, Lee JW, Yeom JS, et al. A practical MRI grading system for lumbar foraminal stenosis. AJR Am J Roentgenol 2010;194(4):1095–8.
[15] Weishaupt D, Zanetti M, Boos N, Hodler J. MR imaging and CT in osteoarthritis of the lumbar facet joints. Skeletal Radiol 1999;28(4):215–19.
[16] Pathria M, Sartoris DJ, Resnick D. Osteoarthritis of the facet joints: accuracy of oblique radiographic assessment. Radiology 1987;164(1):227–30.
[17] Spondylolisthesis Meyerding HW. Surg Gynecol Obstet 1932;54:371–7.
[18] Bolender NF, Schonstrom NS, Spengler DM. Role of computed tomography and myelography in the diagnosis of central spinal stenosis. J Bone Joint Surg Am 1985;67(2):240–6.
[19] Winder MJ, Gambhir S. Comparison of ALIF vs. XLIF for L4/5 interbody fusion: pros, cons, and literature review. J Spine Surg 2016;2(1):2–8.
[20] Hrabalek L, Adamus M, Gryga A, Wanek T, Tucek P. A comparison of complication rate between anterior and lateral approaches to the lumbar spine. Biomed Pap Med Fac Univ Palacky Olomouc Czech Repub 2014;158(1):127–32.
[21] Gammal ID, Spivak JM, Bendo JA. Systematic review of thigh symptoms after lateral transpsoas interbody fusion for adult patients with degenerative lumbar spine disease. Int J Spine Surg 2015;9:62.
[22] Cummock MD, Vanni S, Levi AD, Yu Y, Wang MY. An analysis of postoperative thigh symptoms after minimally invasive transpsoas lumbar interbody fusion. J Neurosurg Spine 2011;15(1):11–18.
[23] Tessitore E, Molliqaj G, Schaller K, Gautschi OP. Extreme lateral interbody fusion (XLIF): a single-center clinical and radiological follow-up study of 20 patients. J Clin Neurosci 2017;36:76–9.
[24] Wang TY, Nayar G, Brown CR, Pimenta L, Karikari IO, Isaacs RE. Bony lateral recess stenosis and other radiographic predictors of failed indirect decompression via extreme lateral interbody fusion: multi-institutional analysis of 101 consecutive spinal levels. World Neurosurg 2017;106:819–26.
[25] Lang G, Perrech M, Navarro-Ramirez R, et al. Potential and limitations of neural decompression in extreme lateral interbody fusion-A systematic review. World Neurosurg 2017;101:99–113.
[26] Kepler CK, Sharma AK, Huang RC, et al. Indirect foraminal decompression after lateral transpsoas interbody fusion. J Neurosurg Spine 2012;16(4):329–33.
[27] Sanderson SP, Houten J, Errico T, Forshaw D, Bauman J, Cooper PR. The unique characteristics of "upper" lumbar disc herniations. Neurosurgery 2004;55(2):385–9 discussion 389.
[28] Kim DS, Lee JK, Jang JW, Ko BS, Lee JH, Kim SH. Clinical features and treatments of upper lumbar disc herniations. J Korean Neurosurg Soc 2010;48(2):119–24.
[29] Pierro A, Cilla S, Maselli G, Cucci E, Ciuffreda M, Sallustio G. Sagittal normal limits of lumbosacral spine in a large adult population: a quantitative magnetic resonance imaging analysis. J Clin Imaging Sci 2017;7:35.