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Original Article

Preoperative Diffusion Tensor Imaging Guided Surgical Planning Versus Standard MRI for Reducing Iatrogenic Nerve Injury in Spinal Fusion Surgery

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ABSTRACT

Background: Iatrogenic neurological injury remains an important complication of complex lumbar and lumbosacral spinal fusion. Conventional magnetic resonance imaging (MRI) provides detailed anatomical information but limited characterization of the microstructural organization and trajectories of compressed or displaced nerve fibers. Diffusion tensor imaging (DTI) may provide additional patient-specific information for surgical planning. Objective: To evaluate whether preoperative DTI-guided surgical planning reduces postoperative neurological deficits and improves early clinical outcomes compared with standard MRI-based planning. Methods: This prospective parallel-group randomized controlled trial included 92 adults undergoing elective multilevel lumbar or lumbosacral spinal fusion. Participants were randomized 1:1 to DTI-guided planning (n=46) or standard MRI planning (n=46). Four participants were lost to six-week follow-up, leaving 44 participants per group for postoperative analysis. Outcomes included neurological deficits, Medical Research Council (MRC) motor scores, sensory recovery, visual analog scale (VAS) pain scores, and Oswestry Disability Index (ODI). Results: Neurological deficits occurred in 1/44 participants (2.3%) in the DTI group and 8/44 (18.2%) in the standard MRI group, corresponding to a risk difference of −15.9 percentage points (95% CI −28.1 to −3.7), relative risk 0.13 (95% CI 0.02–0.96), and p=0.030. Mean postoperative MRC scores were 4.82±0.39 and 4.38±0.65, respectively (mean difference 0.44; 95% CI 0.21–0.67; p<0.001). At six weeks, VAS pain was 15.2 mm lower and ODI 11.8 percentage points lower in the DTI group. Conclusion: DTI-guided planning was associated with fewer short-term neurological deficits and greater early functional recovery than standard MRI planning. Keywords: Diffusion Tensor Imaging; Iatrogenic Nerve Injury; Magnetic Resonance Imaging; Spinal Fusion; Tractography.

INTRODUCTION

Spinal fusion is widely used for the management of degenerative instability, spondylolisthesis, spinal stenosis, deformity, and other disorders requiring restoration of spinal stability when appropriately selected conservative strategies have failed. Despite substantial advances in operative technique, navigation, instrumentation, and perioperative monitoring, neurological complications remain among the most consequential adverse outcomes of spinal surgery. Nerve-root or plexus injury may arise from direct mechanical injury, excessive traction, displacement during correction, cage or screw placement, ischemic mechanisms, or manipulation of neural structures within anatomically restricted operative corridors. Contemporary evidence demonstrates that the

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frequency of neurological complications varies considerably according to surgical approach, disease complexity, number of treated levels, and the extent of anatomical distortion, with particularly high-risk subgroups encountered in complex fusion and deformity surgery (1). Intraoperative neurophysiological monitoring provides important real-time information regarding impending neural dysfunction and has substantial diagnostic accuracy, particularly when motor-evoked potentials or multimodal techniques are used; however, neuromonitoring identifies physiological changes after surgical manipulation has begun and cannot fully substitute for precise preoperative delineation of individual neural anatomy (2).

Conventional magnetic resonance imaging remains central to the preoperative evaluation of degenerative lumbar pathology because high-resolution anatomical sequences effectively demonstrate intervertebral discs, spinal canal dimensions, foraminal narrowing, soft tissues, gross nerve-root compression, and other structural abnormalities. Nevertheless, anatomical MRI predominantly depicts macroscopic morphology and may be insufficient for defining the microstructural state or complete trajectory of individual compressed and displaced neural fibers, particularly in patients with severe stenosis, multilevel disease, anatomical deformity, or complex operative corridors. Diffusion tensor imaging extends conventional MRI by characterizing the directionality of water diffusion within neural tissue and generating quantitative parameters such as fractional anisotropy and apparent diffusion coefficient. Diffusion tensor tractography further permits reconstruction of probable three-dimensional neural pathways, providing information that may complement conventional structural imaging in surgically amenable spinal pathology (3,4).

A growing body of evidence demonstrates that lumbar nerve-root compression produces measurable abnormalities in diffusion parameters. A systematic review and meta-analysis of diffusion tensor imaging in lumbar disc herniation found significantly lower fractional anisotropy and higher apparent diffusion coefficient values in compressed nerve roots than in contralateral unaffected roots, supporting the ability of DTI to characterize microstructural neural impairment that is not fully represented by conventional anatomical sequences (5). Recent clinical work using 3.0-T DTI has similarly shown that compressed lumbosacral roots demonstrate lower fractional anisotropy, higher apparent diffusion coefficients, deformation, displacement, and partial tract disruption, suggesting potential value for both diagnostic localization and preoperative characterization (6). Prospective clinical studies have also demonstrated associations between diffusion parameters and pain, neurological symptoms, and disability in patients with lumbar disc herniation and radiculopathy (7). Advanced multimodal MRI research incorporating DTI, diffusion-weighted imaging, and T2 mapping has further demonstrated relationships between diffusion abnormalities, pain severity, electrophysiological findings, and markers of axonal or myelin-related dysfunction (8).

The feasibility of reconstructing the lumbosacral plexus and lumbar nerve roots has improved with advances in diffusion acquisition and tractographic processing. Three-dimensional magnetic resonance tractography of the lumbosacral plexus can be achieved using optimized diffusion protocols and anatomically defined seed regions, although diffusion metrics differ across spinal levels and technically challenging regions (9). Prospective studies of patients undergoing lumbar decompression have demonstrated that fractional anisotropy values and tractographic appearances can change after surgical treatment and may parallel clinical recovery, indicating that diffusion parameters are sensitive to alterations in compressed neural tissue over time (10). Preoperative DTI has also shown prognostic potential; in a prospective study of 117 patients undergoing surgery for lumbar disc herniation, affected-side fractional anisotropy demonstrated strong discrimination between favorable and unfavorable postoperative outcome groups, suggesting that microstructural nerve integrity may contain clinically relevant prognostic information (11). Beyond degenerative lumbar disease, preoperative diffusion tractography has been investigated in spinal intramedullary tumors, where tract configuration has informed assessments of resectability, operative planning, and preservation of neurological function (12).

The clinical question increasingly extends beyond diagnosis toward whether diffusion-derived neural visualization can alter surgical strategy and reduce preventable neural injury. A 2024 retrospective case-control study specifically evaluated preoperative DTI for mitigating nerve injury during extreme lateral interbody fusion, reflecting growing interest in translating diffusion tractography into perioperative risk reduction (13). DTI-guided localization has also been applied during percutaneous endoscopic lumbar discectomy, where targeted surgery based on diffusion-defined responsible nerve roots was associated with shorter operating time and lower intraoperative blood loss while achieving clinical outcomes comparable with more extensive decompression (14).

Complementary navigation research has demonstrated that segmentation and fusion of MRI-defined neural anatomy with CT-defined osseous structures can delineate individualized safe corridors for percutaneous lumbar interbody fusion, illustrating the broader principle that direct visualization of patient-specific neural anatomy may enhance procedural planning beyond reliance on population-based anatomical landmarks alone (15). Intraoperative navigation itself has become increasingly integrated into spinal surgery because accurate visualization of instrumentation trajectories may improve technical precision, although effects on complication and reoperation rates vary according to procedure and patient population (16).

Despite these developments, substantial uncertainties remain. Modern reviews conclude that spinal DTI is promising for surgical decision-making, disease characterization, outcome assessment, and prognosis, but emphasize heterogeneity in acquisition protocols, reconstruction methods, study populations, outcome definitions, and follow-up periods (3,4). Technical standardization is particularly important because image quality and tract reconstruction can be influenced by field strength, motion, susceptibility effects, diffusion direction number, region-of-interest placement, fiber-tracking thresholds, and post-processing algorithms. Recent work applying convolutional neural networks to lumbar nerve DTI reconstruction illustrates continuing efforts to automate segmentation and improve reproducibility, but these technologies remain under active development rather than established components of routine spinal practice (17). Consequently, the evidence base remains stronger for diagnostic and microstructural characterization than for directly demonstrating that preoperative DTI reduces surgical neurological injury.

The present randomized controlled trial was therefore designed to compare preoperative DTI-guided surgical planning with conventional MRI-based planning in adults undergoing multilevel lumbar or lumbosacral spinal fusion. The primary objective was to determine whether DTI-guided planning reduced the incidence of new or worsened postoperative neurological deficits. Secondary objectives were to evaluate postoperative motor strength, sensory recovery, radicular pain, and functional disability during the six-week postoperative period. The underlying hypothesis was that individualized visualization of neural trajectories before instrumentation would provide additional anatomical information capable of facilitating safer surgical corridor selection and reducing neural injury while improving early postoperative recovery.

MATERIALS AND METHODS

This prospective, parallel-group randomized controlled trial was conducted at tertiary neurosurgical clinical sites in Sindh, Pakistan, from May to December 2025. The trial evaluated the clinical effect of incorporating preoperative diffusion tensor imaging and tractographic reconstruction into surgical planning for adults scheduled to undergo multilevel instrumented lumbar or lumbosacral fusion. Participants underwent baseline evaluation before surgery and postoperative assessments at two and six weeks according to the outcome schedule. The intervention period consisted of the preoperative imaging and surgical planning process, followed by the planned operative procedure and six weeks of clinical follow-up.

Adults aged 35–70 years scheduled for elective multilevel instrumented fusion involving the L2–S1 region were considered eligible. Surgical indications included severe degenerative disc disease, spondylolisthesis, or spinal stenosis associated with persistent radiculopathy or neurogenic claudication that had remained refractory to conservative treatment for at least six months. Patients were excluded if they had previously undergone lumbar fusion, had metallic implants or other conditions precluding high-field MRI, had severe spinal trauma, spinal malignancy, active systemic infection, or a pre-existing permanent motor deficit. These criteria were intended to identify patients undergoing complex degenerative fusion while avoiding conditions in which postoperative neurological assessment would be substantially confounded by pre-existing irreversible motor impairment or incompatible imaging requirements.

A total of 115 patients were assessed for eligibility during the recruitment period. Twenty-three were not enrolled: 15 did not fulfill the eligibility criteria and eight declined participation. Ninety-two participants subsequently entered the randomized comparison. Randomization was performed in a 1:1 ratio using a computer-generated block randomization scheme with variable block sizes of four and six. Allocation concealment was maintained through sequentially numbered, opaque, sealed envelopes opened by an independent study coordinator before the preoperative imaging and surgical-planning phase. Forty-six participants were allocated to DTI-guided surgical planning and 46 to standard MRI-based planning.

Complete blinding of the operating surgeon was not feasible because the intervention consisted of additional imaging information used directly during preoperative surgical planning. However, blinding was maintained for postoperative outcome evaluators, radiologists responsible for postoperative imaging assessment, and statistical evaluators. This arrangement was intended to reduce ascertainment and analytical bias while recognizing that surgeon masking would have prevented delivery of the intervention itself.

Participants allocated to the standard MRI group underwent conventional preoperative 3.0-T anatomical MRI. The imaging protocol included T1-weighted, T2-weighted, and proton-density-weighted axial and sagittal acquisitions. Surgical trajectories, screw positioning, operative corridors, and interbody cage dimensions were planned using these conventional anatomical images. Participants allocated to the DTI group underwent the same conventional MRI protocol supplemented by high-resolution diffusion tensor acquisition using 32 diffusion-sensitizing gradient directions. Color-coded three-dimensional tractographic reconstructions of relevant lumbosacral neural pathways were generated and fused with T2-weighted anatomical information. Three-dimensional lumbosacral tract reconstruction is technically feasible and has been increasingly investigated as a method for defining individualized neural trajectories (9).

The DTI reconstructions were used by operating surgeons to assess displacement, entrapment, and probable microstructural trajectories of exiting nerve roots during preoperative planning. The information was incorporated into decisions concerning surgical corridor selection, retractor positioning, instrumentation trajectory, and avoidance of visualized neural bundles. This approach was consistent with emerging surgical applications in which diffusion tractography or multimodal image fusion is used to better delineate functionally important neural structures before intervention (12-15). DTI was therefore used as an adjunct rather than a replacement for conventional anatomical imaging.

All surgical procedures in both study groups were performed using comparable microsurgical principles and continuous intraoperative neurophysiological monitoring. Contemporary evidence indicates that motor-evoked potentials and multimodal monitoring have useful diagnostic accuracy for identifying intraoperative neurological compromise, although their effectiveness and optimal use vary among different categories of spinal surgery (2). Standardization of operative monitoring across both treatment groups was intended to reduce systematic differences in intraoperative neural surveillance unrelated to the preoperative imaging strategy.

Neurological evaluation focused on new or worsened lower-extremity deficits and motor function. Muscle strength was graded using the Medical Research Council 0–5 scale. The MRC scale is widely used for clinical manual muscle testing and has demonstrated substantial inter-rater and intra-rater reliability in trained observers, although categorical distinctions at higher strength grades require careful interpretation (18). Motor assessments were obtained at baseline and six weeks after surgery. Sensory function was similarly evaluated at baseline and at the six-week postoperative assessment, and sensory recovery was recorded as a postoperative clinical outcome.

Radicular pain was measured using a 0–100-mm visual analog scale. Functional disability was assessed using the Oswestry Disability Index on a 0–100% scale, with higher values representing greater disability. The ODI is one of the most extensively used disease-specific disability measures in lumbar spinal disorders and has demonstrated good internal consistency and acceptable construct validity in large populations undergoing lumbar spinal surgery (19). Pain and ODI assessments were obtained at baseline, two weeks, and six weeks following surgery, permitting evaluation of early postoperative recovery patterns in addition to the final six-week comparison.

Four participants were unavailable for the complete six-week follow-up. Two participants assigned to the DTI group were lost following geographical relocation, while two participants in the standard MRI group withdrew consent. Consequently, all 92 randomized participants were retained for baseline descriptive comparisons, whereas postoperative analyses for outcomes requiring six-week observations were based on the 88 participants with available follow-up data, comprising 44 participants in each study arm. Because six-week outcome values were unavailable for the four participants lost to follow-up and no supported imputation procedure was available, postoperative analyses were treated as available-case analyses rather than being described as complete intention-to-treat analyses.

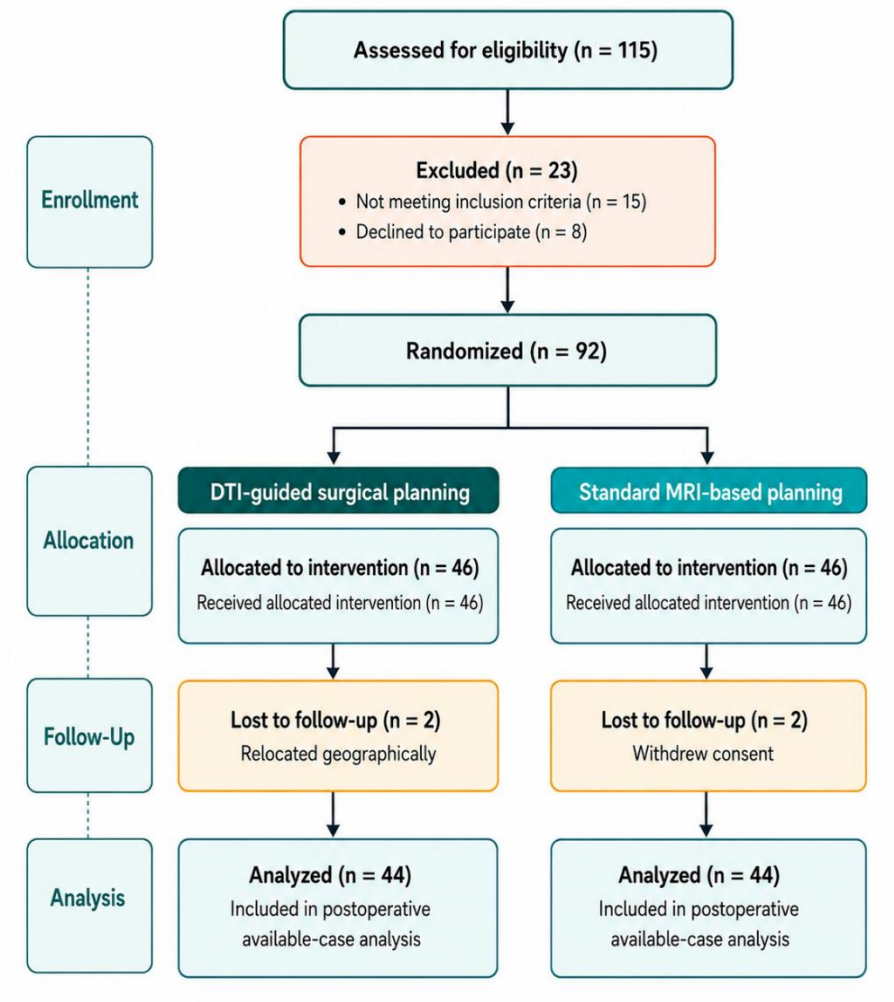

Figure 1 CONSORT Flowchart

Continuous variables were summarized as mean±standard deviation and categorical variables as frequencies and percentages. The Shapiro-Wilk test was used to evaluate normality of continuous measurements. Baseline continuous variables were compared between randomized groups using independent-samples t tests, and categorical variables were compared using tests appropriate to the observed cell distributions. Changes from baseline to six weeks within each treatment group were examined using paired comparisons based on the reported change-score data. Between-group effects for continuous postoperative outcomes were expressed as mean differences with 95% confidence intervals whenever derivable from the reported means, standard deviations, and denominators.

For binary postoperative neurological outcomes with small cell frequencies, Fisher's exact test was used. Absolute risk differences with 95% confidence intervals were calculated, and the primary neurological-deficit comparison was additionally expressed as a relative risk with a 95% confidence interval. Statistical significance was defined using two-sided $p<0.05$. Statistical interpretation emphasized between-group effect estimates and confidence intervals rather than relying exclusively on within-group significance testing. Analyses requiring unavailable underlying output, including the originally proposed repeated-measures model statistics and correlation coefficient between preoperative fractional anisotropy and postoperative pain, were not retained as inferential findings because the numerical statistics required for reproducible reporting were unavailable.

RESULTS

During the study period from May to December 2025, 115 prospective participants were screened for eligibility. Fifteen were excluded because they did not satisfy the eligibility criteria and eight declined participation, leaving 92 patients who underwent random allocation. Forty-six were allocated to DTI-guided surgical planning and 46 to conventional MRI-based planning. Two participants in each group did not complete the six-week follow-up, yielding

44 participants with available postoperative outcome data in each group and an overall six-week follow-up cohort of 88 participants.

Baseline demographic and clinical characteristics were similar between randomized groups. Mean age was 53.8±7.9 years in the DTI group and 53.0±8.6 years in the standard MRI group. Men represented 54.3% of the DTI group and 50.0% of the standard MRI group. Mean body mass index was 27.1±3.0 kg/m^2 and 26.5±3.2 kg/m^2, respectively. Baseline pain severity was substantial in both arms, with mean VAS scores of 74.8±11.2 mm in the DTI group and 73.6±11.9 mm in the standard MRI group. Mean baseline ODI values were 59.1±9.1% and 58.1±9.8%, respectively. The number of surgically treated levels was also similarly distributed. None of the baseline comparisons was statistically significant.

Table 1. Baseline Demographic and Clinical Characteristics of Randomized Participants

Characteristic	Total Sample (N=92)	DTI Group (n=46)	Standard MRI Group (n=46)	p-value
Age, years	53.4±8.2	53.8±7.9	53.0±8.6	0.642
Male, n (%)	48 (52.2)	25 (54.3)	23 (50.0)	0.677
Female, n (%)	44 (47.8)	21 (45.7)	23 (50.0)	—
Body mass index, kg/m²	26.8±3.1	27.1±3.0	26.5±3.2	0.358
Baseline VAS pain, mm	74.2±11.5	74.8±11.2	73.6±11.9	0.619
Baseline ODI, %	58.6±9.4	59.1±9.1	58.1±9.8	0.615
Two surgical levels, n (%)	58 (63.0)	28 (60.9)	30 (65.2)	0.668
Three or more surgical levels, n (%)	34 (37.0)	18 (39.1)	16 (34.8)	—

Data are mean±SD or n (%). DTI, diffusion tensor imaging; MRI, magnetic resonance imaging; VAS, visual analog scale; ODI, Oswestry Disability Index.

At six weeks, new or worsened postoperative neurological deficits occurred in one participant in the DTI-guided group and eight participants in the standard MRI group. These frequencies corresponded to event rates of 2.3% and 18.2%, respectively. The absolute risk difference was −15.9 percentage points (95% CI −28.1 to −3.7), indicating fewer deficits among participants planned with DTI. The estimated relative risk was 0.13 (95% CI 0.02–0.96), and the Fisher exact p-value was 0.030.

Mean postoperative MRC motor strength was 4.82±0.39 in the DTI group compared with 4.38±0.65 in the standard MRI group. The resulting mean difference was 0.44 points (95% CI 0.21–0.67; p<0.001). Sensory recovery was recorded in 41/44 participants (93.2%) in the DTI group and 32/44 participants (72.7%) in the standard MRI group, corresponding to an absolute difference of 20.5 percentage points (95% CI approximately 5.3–35.6; Fisher exact p=0.021).

Table 2. Neurological, Motor, and Sensory Outcomes at Six Weeks

Outcome	DTI Group (n=44)	Standard MRI Group (n=44)	Effect Estimate (95% CI)	p-value
New/worsened neurological deficit, n (%)	1 (2.3)	8 (18.2)	Risk difference −15.9 percentage points (−28.1 to −3.7)	0.030
Relative risk of neurological deficit	—	—	0.13 (0.02–0.96)	—
Postoperative MRC motor score	4.82±0.39	4.38±0.65	Mean difference 0.44 (0.21–0.67)	<0.001
Sensory recovery, n (%)	41 (93.2)	32 (72.7)	Risk difference 20.5 percentage points (5.3–35.6)	0.021

Binary p-values were calculated using Fisher's exact test. MRC, Medical Research Council; CI, confidence interval.

Both treatment groups demonstrated substantial reductions in postoperative pain compared with baseline, although improvement was greater among participants in the DTI-guided group. In the 44 DTI participants with six-week follow-up, mean VAS pain decreased from 74.6±11.1 mm to 21.3±8.4 mm, corresponding to a mean change of −53.3±9.2 mm. In the standard MRI group, VAS decreased from 73.8±11.7 mm to 36.5±10.2 mm, corresponding to a change of −37.3±10.1 mm. The between-group difference in mean change was −16.0 mm, with an approximate 95% CI from −20.1 to −11.9 mm.

Functional disability showed a similar pattern. ODI decreased from 58.9±9.0% at baseline to 19.4±6.8% at six weeks in the DTI group, representing an improvement of −39.5±7.9 percentage points. In the standard MRI group, ODI decreased from 58.3±9.6% to 31.2±8.5%, representing an improvement of −27.1±8.4 percentage points. The between-group difference in improvement was −12.4 percentage points (approximately 95% CI −15.9 to −8.9).

Evaluation of the intermediate two-week assessment demonstrated that separation between groups was already evident early in postoperative recovery. Mean VAS pain at two weeks was 38.2±9.1 mm in the DTI group and 49.4±10.5 mm in the standard MRI group, corresponding to a mean between-group difference of −11.2 mm (95% CI approximately −15.4 to −7.0; p<0.001). At six weeks, the corresponding values were 21.3±8.4 and 36.5±10.2 mm, yielding a difference of −15.2 mm (95% CI approximately −19.2 to −11.2; p<0.001).

Table 3. Changes in Pain and Disability From Baseline to Six Weeks

Outcome	Baseline	Six Weeks	Mean Change	Change (95% CI)	Within-Group p-value
VAS pain, DTI group, mm	74.6±11.1	21.3±8.4	−53.3±9.2	−16.0 (−20.1 to −11.9)	<0.001
VAS pain, standard MRI group, mm	73.8±11.7	36.5±10.2	−37.3±10.1	Reference	<0.001
ODI, DTI group, %	58.9±9.0	19.4±6.8	−39.5±7.9	−12.4 (−15.9 to −8.9)	<0.001
ODI, standard MRI group, %	58.3±9.6	31.2±8.5	−27.1±8.4	Reference	<0.001

Negative change values represent improvement.

ODI at two weeks was 34.1±7.6% in the DTI group and 43.8±8.9% in the standard MRI group, corresponding to a difference of −9.7 percentage points (95% CI approximately −13.2 to −6.2; p<0.001). At six weeks, ODI was 19.4±6.8% and 31.2±8.5%, respectively, with a between-group difference of −11.8 percentage points (95% CI approximately −15.1 to −8.5; p<0.001).

Table 4. Longitudinal Pain and Disability Outcomes

Outcome and Time Point	DTI Group (n=44)	Standard MRI Group (n=44)	Mean Difference, DTI–MRI (95% CI)	p-value
VAS, baseline, mm	74.6±11.1	73.8±11.7	0.8 (−4.0 to 5.6)	0.743
VAS, 2 weeks, mm	38.2±9.1	49.4±10.5	−11.2 (−15.4 to −7.0)	<0.001
VAS, 6 weeks, mm	21.3±8.4	36.5±10.2	−15.2 (−19.2 to −11.2)	<0.001
ODI, baseline, %	58.9±9.0	58.3±9.6	0.6 (−3.3 to 4.5)	0.763
ODI, 2 weeks, %	34.1±7.6	43.8±8.9	−9.7 (−13.2 to −6.2)	<0.001
ODI, 6 weeks, %	19.4±6.8	31.2±8.5	−11.8 (−15.1 to −8.5)	<0.001

At the available six-week endpoint, the DTI-guided group therefore demonstrated a lower observed neurological-deficit rate, higher motor scores, higher recorded sensory recovery, and greater reductions in pain and functional disability. The magnitude of between-group separation in VAS and ODI increased between the two-week and six-week observations, suggesting a persistently different early recovery trajectory rather than an isolated immediate postoperative difference.

DISCUSSION

The principal finding of this randomized controlled trial was that incorporation of preoperative DTI-derived tractography into surgical planning was associated with a lower observed incidence of new or worsened neurological deficit during the first six postoperative weeks compared with planning based on conventional MRI alone. Neurological deficits occurred in 2.3% of participants with available follow-up after DTI-guided planning and 18.2% after standard MRI planning, corresponding to an absolute risk reduction of approximately 15.9 percentage points and an estimated relative risk of 0.13. The DTI group also demonstrated higher postoperative MRC motor scores, a greater proportion of recorded sensory recovery, lower pain scores, and substantially greater improvement in ODI. The differences in pain and disability were present by two weeks and increased further by six weeks, supporting a consistent early postoperative pattern across several clinically relevant outcomes rather than reliance on a single neurological endpoint.

These findings are consistent with the established microstructural behavior of compressed lumbar nerve roots on diffusion imaging. Contemporary meta-analysis shows that nerve roots affected by lumbar disc herniation generally demonstrate reduced fractional anisotropy and increased apparent diffusion coefficients relative to unaffected roots, indicating disruption of directional diffusion within compressed neural tissue (5). Clinical DTI studies have likewise demonstrated localized reductions in fractional anisotropy, increased diffusivity, fiber deformation, and tract discontinuity in patients with lumbosacral nerve-root compression (6,7). Bruno et al. further demonstrated correlations between advanced diffusion measures, clinical pain, and electrophysiological abnormalities, suggesting that diffusion changes contain information concerning the biological consequences of nerve-root compression rather than representing only geometric displacement (8). The present trial extends this diagnostic and physiological evidence toward a surgical-planning context by examining whether visualization of individualized neural trajectories may translate into differences in postoperative clinical outcomes.

The clinical value of DTI in lumbar radiculopathy has increasingly been explored beyond static diagnosis. Prospective postoperative studies have demonstrated increases in fractional anisotropy and improvement of tractographic abnormalities after decompressive procedures, suggesting that diffusion parameters can track changes in neural microstructure following relief of compression (10). Wu et al. reported that preoperative affected-side fractional anisotropy showed strong predictive performance for postoperative surgical outcome in lumbar disc herniation, with higher preoperative FA associated with more favorable recovery (11). These findings support the broader concept that diffusion-derived parameters contain information relevant to both neural integrity and postoperative recovery. However, the present study should not be interpreted as showing that DTI itself improves neural physiology; rather, the plausible therapeutic pathway is that additional preoperative information changed how surgeons planned and navigated areas of potential neural vulnerability.

The neurological outcome observed here is also clinically plausible when considered in relation to contemporary literature on lumbar fusion complications. Neurological injury following spinal fusion is heterogeneous and depends on the operative approach, level, deformity, extent of correction, degree of traction, and anatomical complexity. A recent systematic review of anterior lumbar interbody fusion reported neurological complication rates generally ranging from 4.1% to 7.7%, with substantially higher values reported in certain high-risk anatomical and deformity subgroups (1). These data reinforce that neurological injury is uncommon in many routine procedures but remains clinically important in complex cases because even a relatively low event rate can result in substantial morbidity. The comparatively high deficit rate observed in the standard MRI arm of the present trial may therefore reflect the selected population undergoing multilevel fusion rather than being representative of all lumbar fusion procedures.

Preoperative imaging and intraoperative monitoring address different phases of neurological risk. Neurophysiological monitoring provides continuous or intermittent functional surveillance during surgery and can detect physiological alterations that may signal impending neurological injury. A 2024 systematic review and meta-analysis involving more than 100 studies demonstrated high specificity for somatosensory-evoked potentials, high sensitivity and specificity for motor-evoked potentials, and useful overall performance of multimodal monitoring in detecting intraoperative neurological deterioration (2). Nevertheless, intraoperative monitoring generally indicates functional disturbance after neural structures have been exposed to a potentially harmful maneuver. Preoperative tractographic planning has a different purpose: it attempts to identify individualized neural trajectories before the critical maneuver occurs. These approaches are therefore potentially complementary rather than competing safety strategies.

Evidence regarding the ability of routine neuromonitoring to reduce neurological complications in lumbar procedures remains mixed. In a large analysis of lumbar decompression and fusion procedures, Dodo et al. found that although use of intraoperative neurophysiological monitoring had increased substantially, adjusted and propensity-matched analyses did not demonstrate a significant reduction in neurological deficits across all elective lumbar procedures (20). Similarly, literature on lateral lumbar interbody fusion indicates variability in the performance and clinical value of different monitoring modalities and emphasizes the absence of universal consensus regarding optimal monitoring strategy (21). A standardized LLIF monitoring cohort reported postoperative deficits despite use of neuromonitoring and found that multilevel fusion was associated with greater neurological risk (22). These findings help explain why anatomical risk reduction before instrumentation remains relevant even when continuous intraoperative monitoring is available.

The present intervention also fits within the broader evolution of image-guided spinal surgery. MRI/CT fusion and nerve segmentation have been used to map Kambin's triangle and individualized neural boundaries during percutaneous lumbar fusion, demonstrating that combining osseous and neural imaging can assist in selection of safer trajectories (15). Navigation technologies more broadly permit improved visualization of anatomical relationships and instrumentation trajectories, although the magnitude of benefit on clinical complications varies among procedures (16). DTI-guided planning adds a microstructural neural component to this paradigm. Rather than relying solely on static bony and soft-tissue anatomy, tractography provides an estimate of neural fiber orientation and displacement. The potential benefit is likely to be greatest where the expected anatomy has been distorted by stenosis, deformity, scarring, multilevel degeneration, or other factors that reduce the reliability of conventional landmarks.

Direct evidence for DTI-guided operative targeting is emerging. Lian et al. evaluated DTI-guided localization during percutaneous endoscopic lumbar discectomy and found that targeted single-level treatment based on diffusion localization achieved outcomes similar to more extensive surgery while reducing operative time and blood loss (14). Preoperative DTI has also been investigated specifically as a strategy for mitigating nerve injury during extreme lateral interbody fusion (13). In spinal intramedullary tumors, diffusion tractography has assisted surgical selection and planning by demonstrating fiber displacement and probable tract involvement (12). Although these studies involve different procedures and pathologies, they collectively support the underlying surgical principle that preoperative identification of individualized neural anatomy can alter operative planning.

The pain and disability findings also deserve consideration. At six weeks, the DTI group had a mean VAS score 15.2 mm lower than the standard MRI group and a mean ODI 11.8 percentage points lower. The difference in change from baseline was 16.0 mm for VAS and 12.4 percentage points for ODI. ODI is a validated and internally consistent measure of disability among patients undergoing lumbar spinal surgery and is appropriate for capturing clinically meaningful functional recovery in this population (19). Greater improvement in disability could plausibly result from better preservation of neurological function, less neural irritation, or differences in postoperative radicular symptoms. However, the present trial did not directly measure the mechanistic pathway linking tractographic planning to pain recovery, and these secondary outcomes should therefore be interpreted as clinical associations with the randomized intervention rather than proof of a specific biological mechanism.

The observed sensory and motor findings similarly suggest improved early neurological preservation but require careful interpretation. The mean postoperative MRC difference of 0.44 points favored the DTI group. The MRC scale remains a widely recognized clinical grading system with substantial reliability when used by trained observers (18), but it is ordinal and has limited resolution near the upper grades. Consequently, the clinical significance of a mean difference should be interpreted together with the categorical neurological-deficit outcome rather than in isolation. The sensory-recovery result also favored DTI; however, interpretation depends on the exact population considered eligible for sensory recovery, and future trials should define baseline sensory impairment and recovery criteria prospectively so that the denominator represents participants genuinely at risk for persistent sensory dysfunction.

The technological limitations of DTI remain important. Magnetic resonance tractography does not directly depict individual axons and should not be interpreted as an anatomically infallible representation of nerve fibers. Reconstruction depends on mathematical estimation from diffusion properties and can be affected by noise, motion, susceptibility artifacts, crossing or complex fibers, spatial resolution, diffusion direction number, acquisition time, and operator-defined tracking parameters. Current systematic reviews therefore regard DTI as promising but still insufficiently standardized for unrestricted routine clinical use (3,4). Differences in scanner platforms and reconstruction methods also complicate comparison of absolute diffusion values across institutions.

Reproducibility is particularly relevant for multicenter adoption. Earlier multicenter work demonstrated that diffusion MRI and fiber tractography of the lumbosacral nerves can be performed across centers but emphasized variability and the need for harmonized methodology (23). More recent work has focused on automation of lumbar nerve reconstruction using convolutional neural networks, which may reduce operator dependence and potentially improve consistency of tractographic processing (17). Diffusion-weighted MR neurography techniques have also continued to evolve, with recent studies showing that dedicated diffusion sequences can identify abnormalities in lumbar nerve roots and may complement conventional T2-weighted or contrast-enhanced imaging (24). These developments suggest that technical barriers are being progressively addressed, although further validation is required before assumptions of interchangeability across scanners and institutions are justified.

Longitudinal diffusion imaging may also have value for understanding postoperative neural recovery. Recent longitudinal work has examined microstructural changes in lumbar nerve roots following interventions for degenerative lumbar pathology, indicating that DTI metrics can evolve after treatment rather than representing fixed patient characteristics (25). This is consistent with earlier postoperative observations demonstrating increased fractional anisotropy after decompression (10). Future DTI-guided surgical trials could therefore combine preoperative planning with serial postoperative diffusion imaging to determine whether avoidance of neurological injury is accompanied by measurable preservation or normalization of neural microstructure.

Several methodological strengths support the current findings. The study used prospective randomized allocation with variable block sizes, concealed allocation through sequentially numbered opaque envelopes, and identical conventional MRI acquisition in both groups. Outcome assessors, postoperative radiologists, and statistical evaluators were blinded to treatment allocation. Both groups received continuous intraoperative neurophysiological monitoring, reducing the likelihood that postoperative neurological differences were simply attributable to systematic availability of neural surveillance in one arm but not the other. Baseline characteristics, including age, sex, BMI, pain, disability, and extent of fusion, were similar between groups. The study also assessed pain and disability at both two and six weeks, which demonstrated a coherent temporal pattern of greater improvement in the DTI group.

The use of multiple clinically relevant outcomes represents an additional strength. The principal neurological-deficit endpoint was supported by motor-strength findings, sensory findings, pain measures, and functional disability. The direction of effect was consistently favorable to DTI across these outcomes, reducing concern that the primary result represents an isolated statistical finding. The use of absolute risk difference and relative risk also provides clinically interpretable information that is more informative than a p-value alone. In particular, the absolute difference in neurological deficits indicates the magnitude of separation observed between the two treatment arms during the six-week follow-up period.

Important limitations remain. The study randomized 92 participants, but six-week outcome data were available for 88. Because no supported imputation strategy or complete outcome information was available for the four participants lost to follow-up, the postoperative analysis is best regarded as an available-case analysis rather than a complete intention-to-treat analysis. The losses were balanced between groups, which reduces but does not eliminate the possibility of attrition bias. Future randomized trials should prespecify missing-data handling and retain all randomized participants in the principal analysis wherever possible.

The number of neurological events was also small. Only nine postoperative deficits were observed across both groups. Although the absolute difference was clinically substantial and Fisher's exact testing remained statistically significant, the relative-risk confidence interval was wide, reflecting uncertainty regarding the precise magnitude of treatment effect. The findings therefore provide evidence of a potentially important effect but should not be interpreted as establishing the exact degree of risk reduction expected in broader practice.

Surgeon blinding was impossible because surgeons needed access to DTI tractography for the intervention to have any effect. This creates the possibility of performance effects beyond the anatomical information contained in the tractographic images. Surgeons who were aware that DTI planning was available may have adopted different levels of caution or altered procedural strategies in ways not fully captured by the available dataset. This limitation is inherent in most image-guided surgical trials and emphasizes the importance of blinded outcome assessment and standardized operative protocols.

The six-week follow-up period represents another important limitation. The current findings establish only early postoperative differences and do not address durability of neurological recovery, long-term radicular pain, fusion success, adjacent-segment degeneration, reoperation, delayed neurological symptoms, return to work, or long-term quality of life. Some early neurological deficits may resolve, while other complications may emerge beyond six weeks. Longitudinal follow-up extending to at least 6–12 months would therefore provide a more complete assessment of whether early differences in neurological preservation translate into sustained patient benefit.

The trial was also performed in tertiary centers with access to 3.0-T MRI, diffusion acquisition, tractographic reconstruction, and surgeons capable of interpreting these data during operative planning. Generalizability to institutions without specialized diffusion-processing expertise may therefore be limited. The incremental cost of DTI acquisition, reconstruction, interpretation, and integration into surgical workflows was not evaluated. Routine implementation would require evidence not only of efficacy but also of reproducibility, feasibility, workflow compatibility, and cost-effectiveness.

Further research should therefore focus on adequately powered multicenter randomized trials using harmonized DTI protocols and clearly standardized neurological endpoints. Future studies should prospectively define neurological deficit severity, transient versus persistent injury, baseline sensory impairment, recovery thresholds, and adverse-event adjudication. Prespecified intention-to-treat analysis and missing-data strategies should be

included. Stratification by fusion approach, number of levels, revision status, severity of stenosis, deformity, and baseline neurological impairment could identify the patient groups most likely to benefit.

The interaction between preoperative DTI, contemporary navigation, robotic instrumentation, and multimodal neuromonitoring also warrants investigation. Rather than testing these technologies individually, future studies could evaluate integrated neural-preservation workflows in which DTI provides preoperative microstructural mapping, navigation provides spatial instrumentation guidance, and neuromonitoring provides intraoperative physiological surveillance. Such multimodal approaches may be particularly relevant for revision surgery, severe deformity, high-grade spondylolisthesis, multilevel fusion, and anatomically distorted neural corridors.

Future work should also evaluate automated tract segmentation and quantitative quality-control metrics. Increasing automation may decrease operator-dependent variability and make DTI more practical for routine workflows (17). Validation against surgical anatomy, neurophysiological findings, postoperative neurological outcomes, and other advanced MR neurography techniques will be important to determine when tractography is sufficiently reliable to influence operative decisions.

Taken together, the present findings contribute randomized comparative evidence to an area previously dominated by diagnostic, technical, prognostic, and observational studies. They support the hypothesis that patient-specific tractographic visualization may provide clinically useful information during planning of complex lumbar fusion. However, the evidence should be interpreted as an early efficacy signal rather than proof that DTI-guided planning should be adopted universally. Replication in larger samples, across multiple centers and imaging platforms, with longer follow-up and standardized analysis will be essential to determine the true incremental value of DTI beyond high-quality conventional MRI, navigation, and intraoperative monitoring.

CONCLUSION

Preoperative diffusion tensor imaging-guided surgical planning was associated with a lower observed incidence of new or worsened neurological deficits and greater short-term improvement in motor function, pain, sensory recovery, and disability compared with conventional MRI-based planning in adults undergoing multilevel lumbar or lumbosacral spinal fusion. The results support the potential value of DTI tractography as an adjunct for individualized visualization of vulnerable neural pathways during preoperative planning rather than as a replacement for conventional MRI or intraoperative neurophysiological monitoring. Because the study involved a modest sample, a small number of neurological events, available-case postoperative analysis, and six weeks of follow-up, larger multicenter randomized trials using standardized DTI acquisition, complete intention-to-treat analysis, clearly defined neurological endpoints, and longer-term clinical follow-up are required before routine implementation can be recommended.

REFERENCES

1. Fujii T, Kumar R, Cha J, Bansal A, de Oliveira RG, Louie PK, et al. Neurological complications following anterior lumbar interbody fusion (ALIF): a systematic review. Global Spine J. 2025. doi:10.1177/21925682251349173.
2. Alvi MA, Kwon BK, Hejrati N, Tetreault LA, Evaniew N, Skelly AC, et al. Accuracy of intraoperative neuromonitoring in the diagnosis of intraoperative neurological decline in the setting of spinal surgery—a systematic review and meta-analysis. Global Spine J. 2024. doi:10.1177/21925682231196514.
3. Scullen TA, Milburn J, Aria KM, Mathkour M, Tubbs RS, Kalyvas J. The use of diffusion tensor imaging in spinal pathology: a comprehensive literature review. Eur Spine J. 2024. doi:10.1007/s00586-024-08231-8.
4. Pesesse P, Vanderthommen M, Durieux N, Zubkov M, Demoulin C. Clinical value and reliability of quantitative assessments of lumbosacral nerve root using diffusion tensor and diffusion weighted MR imaging: a systematic review. J Magn Reson Imaging. 2024. doi:10.1002/jmri.29213.
5. Wang N, Sun D, Zhang XY, Xi Z, Li J, Xie L. Nerve abnormalities in lumbar disc herniation: a systematic review and meta-analysis of diffusion tensor imaging. PLoS One. 2022;17(12):e0279499. doi:10.1371/journal.pone.0279499.
6. Cheng H, Lan H, Bao Y, Yin L. Application of magnetic resonance diffusion tensor imaging in diagnosis of lumbosacral nerve root compression. Curr Med Imaging. 2023. doi:10.2174/1573405620666230612122725.

7. Singh R, Khare N, Aggarwal S, Jain M, Kaur S, Singh HD. A prospective study to evaluate the clinical and diffusion tensor imaging correlation in patients with lumbar disc herniation with radiculopathy. Spine Surg Relat Res. 2023. doi:10.22603/ssrr.2022-0159.
8. Bruno F, Marrelli A, Tommasino E, Martinese G, Gagliardi A, Pertici L, et al. Advanced MRI imaging of nerve roots in lumbar radiculopathy due to discoradicular conflict: DWI, DTI, and T2 mapping with clinical and neurophysiological correlations. Radiol Med. 2022. doi:10.1007/s11547-022-01550-0.
9. Ibrahim I, Škoch A, Herynek V, Jiru F, Tintěra J. Magnetic resonance tractography of the lumbosacral plexus. Medicine (Baltimore). 2021;100:e24646. doi:10.1097/MD.0000000000024646.
10. Shi Y, Zhao F, Dou W, Ding H, Zou YF, Feng Y, et al. Quantitative evaluation of intraspinal lumbar disc herniation-related lumbosacral radiculopathy before and after percutaneous transforaminal endoscopic discectomy using diffusion tensor imaging. Spine. 2021. doi:10.1097/BRS.0000000000003925.
11. Wu P, Huang C, Zhao S, Jin A, Shi B. Preoperative quantitative diffusion tensor imaging on the spinal nerve root is a predictor for the surgical outcome of lumbar disc herniation: a prospective study of 117 patients. J Neurosurg Sci. 2021. doi:10.23736/S0390-5616.21.05441-2.
12. Korkmazer B, Kemerdere R, Bas G, Arslan S, Demir B, Batkitar A, et al. The efficacy of preoperative diffusion tensor tractography on surgical planning and outcomes in patients with intramedullary spinal tumor. Eur Spine J. 2023. doi:10.1007/s00586-023-07872-5.
13. An J, Chen J, Wu H, Zhao J, Zhang W. A retrospective case-control study on the effectiveness of preoperative diffusion tensor imaging for mitigating nerve injury in extreme lateral interbody fusion surgery. Spine J. 2024. doi:10.1016/j.spinee.2024.06.017.
14. Lian Z, Gao S, Yu X, Zhang H. Analysis of the curative effect of diffusion tensor imaging-guided percutaneous endoscopic lumbar discectomy. Curr Med Imaging. 2023. doi:10.2174/1573405619666230206113414.
15. Tabarestani TQ, Sykes D, Maquoit G, Wang TY, Ayoub C, Shaffrey C, et al. Novel merging of CT and MRI to allow for safe navigation into Kambin's triangle for percutaneous lumbar interbody fusion—initial case series investigating safety and efficacy. Oper Neurosurg. 2023. doi:10.1227/ons.0000000000000531.
16. Shuman WH, Valliani AA, Chapman E, Martini ML, Neifert SN, Baron RB, et al. Intraoperative navigation in spine surgery: effects on complications and reoperations. World Neurosurg. 2022. doi:10.1016/j.wneu.2022.01.035.
17. Masumoto R, Eguchi Y, Takeuchi H, Inage K, Narita M, Shiga Y, et al. Automatic generation of diffusion tensor imaging for the lumbar nerve using convolutional neural networks. Magn Reson Imaging. 2024;110237. doi:10.1016/j.mri.2024.110237.
18. Paternostro-Sluga T, Grim-Stieger M, Posch M, Schuhfried O, Vacariu G, Mittermaier C, et al. Reliability and validity of the Medical Research Council scale and a modified scale for testing muscle strength in patients with radial palsy. J Rehabil Med. 2008. doi:10.2340/16501977-0235.
19. Koivunen K, Widbom-Kolhanen S, Pernaa K, Arokoski J, Saltychev M. Reliability and validity of Oswestry Disability Index among patients undergoing lumbar spinal surgery. BMC Surg. 2024. doi:10.1186/s12893-023-02307-w.
20. Dodo Y, Okano I, Zelenty WD, Paek S, Sarin M, Haffer H, et al. The utilization of intraoperative neurophysiological monitoring for lumbar decompression and fusion surgery in New York State. Spine. 2023. doi:10.1097/BRS.0000000000004603.
21. Alluri R, Mok J, Vaishnav AS, Shelby T, Sivaganesan A, Hah RJ, et al. Intraoperative neuromonitoring during lateral lumbar interbody fusion. Neurospine. 2021. doi:10.14245/ns.2142440.220.
22. Mundis GM, Record N, Shah B, Lakomkin N, Carnelian A, Brady KC, et al. Incidence of postoperative neurological deficit with the use of an intraoperative neuromonitoring protocol for lateral lumbar interbody fusion. J Neurosurg Spine. 2023. doi:10.3171/2023.9.SPINE23263.
23. Haakma W, Hendrikse J, Uhrenholt L, Leemans A, Boel LWT, Pedersen M, et al. Multicenter reproducibility study of diffusion MRI and fiber tractography of the lumbosacral nerves. J Magn Reson Imaging. 2018;48(4):951-963. doi:10.1002/jmri.25964.
24. Yoon NY, Ha D, Lee SM, Choi HJ. Diffusion-weighted MR neurography with unidirectional motion-probing gradient to evaluate lumbar nerve roots at 1.5T MR. J Korean Soc Radiol. 2024. doi:10.3348/jksr.2023.0052.
25. Monti L, Bellini M, Alberti M, Piane E, Casseri T, Sadotti G, et al. Longitudinal DTI analysis of microstructural changes in lumbar nerve roots following interspinous process device placement. Magn Reson Imaging. 2024. doi:10.1016/j.mri.2024.110306.