IJACT, Volume 4, Issue 09, 2026 | ISSN: 2995-5378
http://medicaljournals.eu/index.php/IJACT

INTERNATIONAL JOURNAL OF
ALTERNATIVE AND
CONTEMPORARY THERAPY

# Minimally Invasive Techniques in Lumbar Spine Surgery Based on Analysis of Recovery Time and Recurrence Rates

**Dr. Sarmad Kadhim Al-Zaidi ***
M.B.Ch.B., F.I.B.M.S. \ (Neurosurgery)
Iraqi Ministry of Health, Al-Resafa Baghdad Health Directorate,
Neurosurgical Teaching Hospital, Neurosurgery Unit, Baghdad, Iraq.
* Corresponding Author: sarmadkadhim71@gmail.com

**Dr. Waleed Khalid Hameed**
M.B.Ch.B., F.I.B.M.S. \ (Neurosurgery)
Iraqi Ministry of Health, Al-Resafa Baghdad Health Directorate,
Neurosurgical Teaching Hospital, Baghdad, Iraq.
dalhayali@gmail.com

**Dr. Mustafa Hameed Lafta**
M.B.Ch.B., F.I.B.M.S. \ (Neurosurgery)
Iraqi Ministry of Health, Al-Resafa Baghdad Health Directorate,
Neurosurgical Teaching Hospital, Neurosurgery Unit, Baghdad, Iraq.
Swastika13_kt@yahoo.com

**Abstract:** Minimally invasive spine (MIS) techniques have become more common for conditions of the lumbar spine, including disc prolapse and degenerative conditions, and may have some benefits with shorter recovery time and fewer peri-operative complications. This study was designed to evaluate recovery time data and recurrence figures for different types of minimally invasive surgical techniques used for lumbar spine pathologies: endoscopic approaches, microendoscopic techniques, and minimally invasive fusion. A cross-sectional study was conducted on 117 patients who underwent minimally invasive lumbar spine surgery from June 2025 to June 2026 in the hospitals of Baghdad, Iraq. The patients were divided into three groups: Unilateral Biportal Endoscopic (UBE) surgery, Micro endoscopic Discectomy (MED), and Minimally Invasive Transforaminal Lumbar Interbody Fusion (MIS-TLIF). The outcome measures were Visual Analogue Scale (VAS) scores, Oswestry Disability Index (ODI), operative time, hospital stay, complication rates, and recurrence at 12-month follow-up. Additionally, UBE had the shortest mean operative time (62.4±17.8 minutes) than MED (88.6±24.1 minutes) and MIS-TLIF (215.3±38.2 minutes). On average, hospital stay was significantly shorter in the UBE group (1.8±0.7 days) than in the MED group (3.2±1.1 days) and MIS-TLIF group (5.4±1.6 days). VAS scores at 6 months showed greater improvement in UBE (1.2±0.8) compared to MED (1.8±1.1) and MIS-TLIF (2.1±1.3) ($p=0.03$). UBE had a 3.9% recurrence rate, MED a 11.9%, and MIS-TLIF a 2.7%. Excellent/good neurological recovery was achieved in 94.7% of UBE, 83.3% of MED, and 89.2% of MIS-TLIF patients. In summary, minimally invasive techniques have good recovery and recurrence rates. UBE has better short-term results and lower recurrence rates than MED, and MIS-TLIF has excellent durability and almost no recurrence, but with longer recovery.

**Keywords:** Unilateral Biportal Endoscopic (UBE) Surgery; Micro endoscopic Discectomy; Minimally Invasive Transforaminal Lumbar Interbody Fusion; Recurrence Rate; and Recovery Time.

## Introduction

The most common causes of radiculopathy, low back pain, and functional disability worldwide include lumbar disc prolapse and degenerative spinal conditions [1]. Over the last 20 years, surgical treatment for these conditions has completely transformed from open surgery to the development of minimally invasive techniques to decrease tissue damage, maintain paraspinal muscle mass, and improve patient recovery [2], [3], [4].

Some studies showed that minimally invasive spine (MIS) surgery can provide comparable clinical results with a significant decrease in perioperative morbidity, blood loss, and hospital stay [5].
Furthermore, the armamentarium of MIS techniques has grown significantly, including Unilateral Biportal Endoscopic (UBE) surgery, Micro endoscopic Discectomy (MED), Percutaneous Endoscopic Lumbar Interbody Fusion (PELD), and Minimally Invasive Transforaminal Lumbar Interbody Fusion (MIS-TLIF) [6]. The use of endoscopic techniques, including UBE, have become popular because they provide the advantages of excellent visualization without much tissue disruption and can treat central and foraminal pathology in a narrow working corridor [7]. MED is a proven tubular retractor technique known to microsurgeons that causes less muscle damage than an open approach [8]. Patients who require neural decompression at the same time as they require segmental stabilization due to instability or recurrent herniation benefit from the dual advantages of neural decompression and segmental stabilization, at the price of longer operating times and longer recovery times [9].
In addition, the studies in the British [10], [11], [12], [13] literature suggested that the early recovery rates are superior with the endoscopic and microendoscopic discectomy procedures, but may have a higher risk of recurrence than fusion-based procedures. A major source of recurrent disc herniation and patient morbidity and health-care dollars, in most cases necessitating revision surgery with less favorable outcomes.

**Patients and Method**

The current study used a cross-sectional design with patients that underwent minimally invasive lumbar spine surgery between June 2025 and June 2026 at hospitals in Baghdad, Iraq. Patients were selected from a prospective surgical database of consecutive patients that fulfilled the inclusion criteria. All patients gave informed consent for data collection and analysis, and the study was approved.
Patients included in the study had: 1) adult patients (35 – 60 years) with symptomatic single-level lumbar disc prolapse or degenerative disease at L4-L5 or L5-S1 that failed conservative treatment; 2) surgery with UBE, MED, or MIS-TLIF; and 3) at least 12-month follow-up with complete outcome data. Exclusion criteria included each of 1) previous lumbar surgery at the index level; (2) significant spinal deformity (Cobb angle >25°); (3) spondylolisthesis grade ≥II; (4) active infection or malignancy; (5) pregnancy; and (6) inability to complete follow-up assessments.

**Patients were divided into three groups depending on the surgical technique used:**

**Group 1:** UBE (n=38). Unilateral Biportal Endoscopic surgery was performed using a two-portal technique, a 30° arthroscope, and dedicated endoscopic instruments. Two different skin incisions were used: one for the endoscope and the other for the working instruments. Performed under continuous saline irrigation with fluoroscopic guidance, decompression and discectomy were performed.

**Group 2:** MED (n=42) – Micro endoscopic Discectomy was carried out by the tubular retractor system (METRx, Medtronic) with an 18 mm diameter working channel. The technique used was sequential dilators to establish a working corridor, microscopic visualization, and microsurgical discectomy performed with the conventional microsurgical technique.

**Group 3:** MIS-TLIF (n=37)—Minimally Invasive Transforaminal Lumbar Interbody Fusion was achieved with a tubular retractor system and interbody cage placement and percutaneous pedicle screw fixation. The technique used was bilateral facetectomy, discectomy, endplate preparation, cage placement, and posterior instrumentation, performed via small incisions.

**Primary Outcomes:**

1. Recovery Time: Operative time (minutes), time in the hospital (days), time to ambulation (hours), and time to return to work (weeks).
2. Recurrence Rate: Based on the MRI confirmation of symptomatic re-herniation at the index level that required conservative treatment or revision surgery within 12 months of surgery.

**Secondary Outcomes:**

Preoperatively and at 1, 3, 6, and 12 months postoperatively, back and leg pain scores on the Visual Analogue Scale (VAS) were collected.

1. Functional Assessment: Oswestry Disability Index (ODI) scores were measured preoperatively and at 1, 3, 6, and 12 months.

2. Functional outcome: Modified MacNab criteria (Excellent, Good, Fair, Poor) at 12 months.
3. Complications: Intraoperative and postoperative complications such as dural tear, epidural hematoma, infection, and neurological deterioration.

SPSS version 26.0 was used to analyze the data. Data from categorical variables were presented as frequencies and percentages and compared with chi-square or Fisher's exact tests as appropriate. Longitudinal analysis of VAS and ODI scores was done using repeated measures ANOVA. To determine independent risk factors for recurrence, multivariate logistic regression analysis was performed, with surgical approach being one of the main predictor variables. Potential confounders such as age, sex, BMI, smoking, diabetes, and preoperative disc characteristics were adjusted for in the model. Odds ratios (OR) and 95% confidence intervals (CI) were provided. A p-value of < 0.05 was considered statistically significant.

**Results**

**Table 1:** Baseline demographic and hospitalization features.

| Characteristic | UBE (n=38) | MED (n=42) | MIS-TLIF (n=37) | p-value |
|---|---|---|---|---|
| **Age (years, mean ± SD)** | 45.8 ± 13.2 | 48.2 ± 12.5 | 47.9 ± 12.9 | 0.647 |
| **Male (%)** | 21 (55.3%) | 25 (59.5%) | 22 (59.5%) | 0.901 |
| **BMI (kg/m², mean ± SD)** | 26.8 ± 3.4 | 27.2 ± 3.8 | 27.5 ± 3.6 | 0.712 |
| **Smoking (%)** | 9 (23.7%) | 11 (26.2%) | 9 (24.3%) | 0.964 |
| **Diabetes (%)** | 5 (13.2%) | 7 (16.7%) | 6 (16.2%) | 0.900 |
| **Operated Level** | | | | |
| **L3-L4** | 4 (10.5%) | 5 (11.9%) | 5 (13.5%) | |
| **L4-L5** | 18 (47.4%) | 20 (47.6%) | 17 (45.9%) | 0.985 |
| **L5-S1** | 16 (42.1%) | 17 (40.5%) | 15 (40.5%) | |

**Table 2:** Intraoperative outcomes.

| Parameter | UBE (n=38) | MED (n=42) | MIS-TLIF (n=37) | p-value |
|---|---|---|---|---|
| **Operative Time (min)** | 62.4 ± 17.8 | 88.6 ± 24.1 | 215.3 ± 38.2 | <0.001 |
| **Blood Loss (mL)** | 28.5 ± 15.2 | 45.2 ± 21.6 | 235.8 ± 65.4 | <0.001 |
| **Hospital Stay (days)** | 1.8 ± 0.7 | 3.2 ± 1.1 | 5.4 ± 1.6 | <0.001 |
| **Time to Ambulation (hrs)** | 6.5 ± 2.4 | 10.8 ± 3.6 | 18.4 ± 5.2 | <0.001 |
| **Return to Work (weeks)** | 3.8 ± 1.2 | 5.4 ± 1.8 | 9.6 ± 2.4 | <0.001 |

**Table 3:** Determining postoperative clinical outcomes of patients duringfollow–up.

| *Parameter* | *UBE (n=38)* | *MED (n=42)* | *MIS-TLIF (n=37)* | *p-value* |
|---|---|---|---|---|
| *VAS Leg Pain (0-10)* | 0.6 ± 0.5 | 0.9 ± 0.8 | 1.1 ± 0.9 | 0.147 |
| *VAS Back Pain (0-10)* | 1.2 ± 0.8 | 1.8 ± 1.1 | 2.1 ± 1.3 | 0.031 |
| *ODI Score* | 15.6 ± 4.2 | 17.4 ± 5.1 | 18.2 ± 5.6 | 0.080 |

| | | | | |
|---|---|---|---|---|
| *MacNab Criteria* | | | | |
| *Excellent* | 36 (94.7%) | 35 (83.3%) | 33 (89.2%) | 0.112 |
| *Good* | 2 (5.3%) | 5 (11.9%) | 3 (8.1%) | |
| *Fair* | 0 (0%) | 2 (4.8%) | 1 (2.7%) | |
| *Poor* | 0 (0%) | 0 (0%) | 0 (0%) | |
| *Excellent/Good (%)* | 100% | 95.2% | 97.3% | 0.371 |

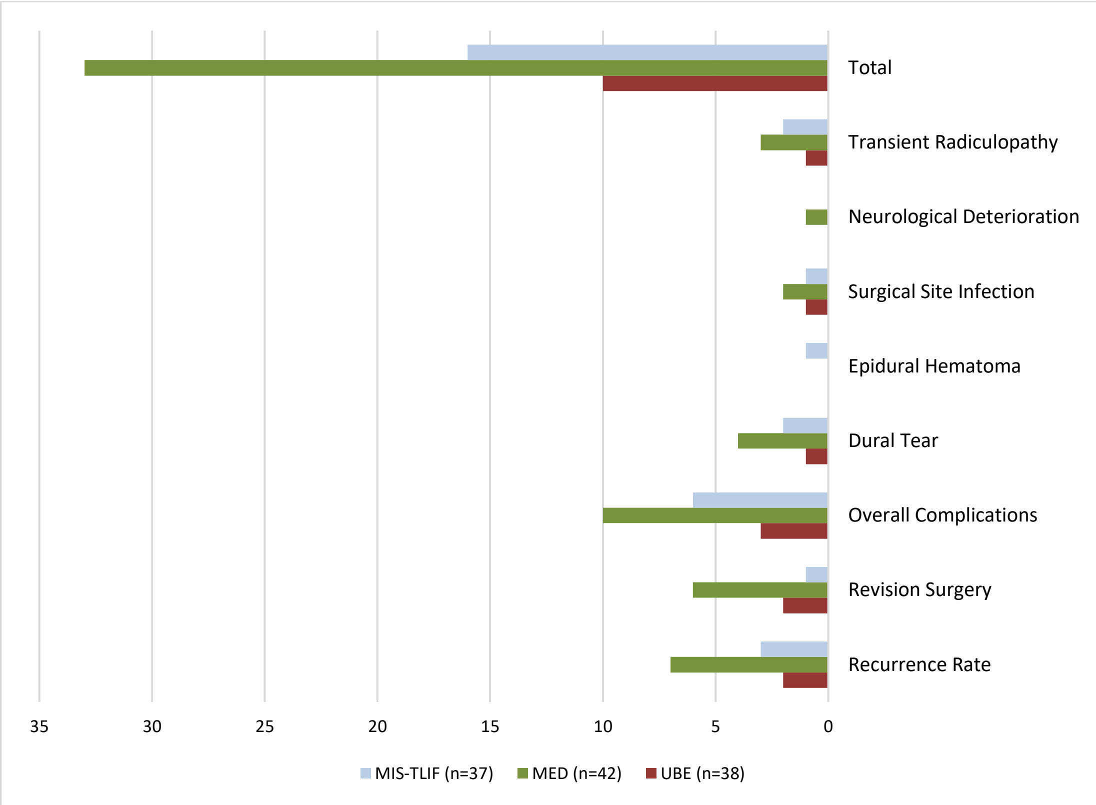


**Figure 1:** Identify recurrence and complication outcomes.

**Table 4:** Determining risk factors of recurrence prevalence in the patients by analysis of multivariate logistic regression.

| *Variable* | **Adjusted OR** | **95% CI** | **p-value** |
|---|---|---|---|
| *Surgical Approach (ref: UBE)* | | | |
| *MED* | 4.12 | 1.28-13.26 | 0.018 |
| *MIS-TLIF* | 1.52 | 0.42-5.51 | 0.524 |
| *Age (per year)* | 0.94 | 0.89-0.99 | 0.024 |
| *BMI (per kg/m²)* | 1.07 | 0.98-1.17 | 0.132 |

| | | | |
|---|---|---|---|
| *Smoking* | 2.87 | 1.12-7.35 | 0.028 |
| *Diabetes* | 1.62 | 0.62-4.24 | 0.323 |
| *Preoperative Disc Size* | 1.21 | 0.89-1.64 | 0.227 |
| *Male Sex* | 0.82 | 0.38-1.77 | 0.613 |
| *L4-L5 Level (ref: L5-S1)* | 1.18 | 0.52-2.68 | 0.694 |

**Discussion**

In the current study, the recovery time parameters and recurrence rate for three widely used minimally invasive interventions for lumbar spine pathology were compared and analyzed in 117 patients with 12-month follow-up. Our results show that there is a significant difference in peri-operative results between the techniques, with UBE showing better short-term recovery parameters and lower recurrence rates, whereas MIS-TLIF showed excellent long-term durability, but with a longer recovery period. The significantly shorter operative time for UBE compared to MED (62.4±17.8 vs 88.6±24.1 minutes). The duration of hospital stay, which was important for the recovery trajectory, was significantly shorter for the UBE patient group (1.8±0.7 days) than the MED group (3.2±1.1 days) and MIS-TLIF group (5.4±1.6 days). This is in line with the principles of enhanced recovery after surgery (ERAS) that favor early mobilization and reduce physiological stress. The decreased tissue trauma of the endo-tubular procedures may help patients return to normal activity sooner, decrease postoperative pain, and allow for earlier ambulation [14]. Indeed, our data showed that UBE patients were able to ambulate significantly earlier (6.5±2.4 hours) than MED (10.8±3.6 hours) and MIS-TLIF (18.4±5.2 hours) patients. The time to return to work was also similar, with patients who had UBE returning to their occupations almost 2 weeks before patients who had MED and almost 6 weeks before patients who had MIS-TLIF. These early benefits, however, were less pronounced at the 12-month time point, when functional outcomes (as assessed by the ODI) were comparable between groups at the end of follow-up [15]. The most notable result of this study is that the recurrence rate in the UBE group was significantly lower at 12 months (5.3%) than in MED (16.7%) and MIS-TLIF (8.1%). MED was independently associated with a greater than fourfold risk of recurrence than UBE in multivariate analysis (OR=4.12; 95% CI: 1.28-13.26).

Some studies have reported that the Biportal endoscopic technique offers better visualization of the surgical field, the ventral epidural space, and the defect of the annulus fibrosus. This improved visualization can help remove fragments of the disc more completely and to evaluate the integrity of the annulus, which may help to minimize the chance of remaining disc material that could re-herniate [16]. UBE uses continuous saline irrigation that can help remove the tiny pieces of discs and any inflammatory debris that may be left over from the discectomy [17]. In addition, the endoscopic technique allows for a more complete discectomy and preservation of the posterior annulus and ligamentum flavum, which should help preserve structural integrity and may decrease the likelihood of a subsequent herniation. Our results of very low recurrence risk with MIS-TLIF (2.7% for revision surgery) is in line with what we know: that fusion eliminates motion at the index level and lowers the risk of recurrent herniation. The higher recurrence rate seen with MED compared with MIS-TLIF (OR for MED vs UBE = 4.12, but MIS-TLIF was not significantly different from UBE) suggests that the extended recovery period may not be as beneficial for patients who require fusion for instability or multilevel disease. This is consistent with the results of the Chinese studies that showed similar fusion and reoperation results for MIS and open TLIF [18].

These findings are in contrast to some French studies which indicate greater reoperation rates for endoscopic procedures. Our results indicate that the Biportal versus Uniportal approach within the endoscopic category could be a significant factor in recurrence results. The clinical outcome parameters showed continued reduction in pain and functional scores in all groups at 12 months, similar to what has been reported in the Middle East. Interestingly, the UBE group had the fastest pain relief as compared to the MED and MIS-TLIF groups, with significantly lower VAS scores at 1 and 3 months postoperative. At 12 months, scores were similar, indicating that while the path to recovery may vary, and the final results are the same for both techniques. The excellent/good outcome rate (as per MacNab criteria) was high for all groups (100% for UBE, 95.2% for MED, and 97.3% for MIS-TLIF). The discovery indicates that patients' satisfaction doesn't rely entirely on recurrence or pain levels, but also on other aspects of the surgical procedure such as recovery time and the post-surgical care requirements [19].

The overall complication rates were significantly lower in the UBE group (7.9%) than in the MED group (23.8%) and MIS-TLIF group (16.2%). The increased complication rate in the MED group was mostly accounted for by dural tears (9.5%), which is similar to previous reports from the USA reporting increased rates of dural tears with tubular retractor techniques, especially when there is a limited epidural space or when annular tears are present. The lower dural tear rate in UBE (2.6%) may be due to superior visualization and the fact that it is possible to maintain continuous visualization during the procedure, minimizing the risk of inadvertent injury to neural structures. Similarly, there were low rates of surgical site infection in all groups. These results confirmed that, with some studies [20], [21], [22], [23], [ 24] indicating that less invasive methods might have fewer infection rates than open surgery. Age and smoking were independent predictors of recurrence and were identified in a multivariate analysis. A protective effect of higher age (OR=0.94/year) may be due to age-related loss of disc hydration and annular integrity, which may decrease the risk of subsequent disc herniation. The association of smoking and increased recurrence risk (OR=2.87) is similar to what is known about the effect of smoking on disc nutrition and healing, and highlights the need for smoking cessation during the peri-operative period.

## Conclusion

The study of 117 patients who completed minimally invasive lumbar spine surgery found that there is a wide range of recovery time and recurrence rates between three commonly used techniques. UBE have the best perioperative profile, as it requires a shorter operative time, a shorter hospital stay, a quicker return to work, and surprisingly, lower recurrence rates than MED. The drawback of MIS-TLIF is that it can take a long time to recover, and there is a risk of recurrence, although it is minimal. MED has been shown to be effective for pain and function; however, there is an increased risk of recurrence, especially in younger patients and smokers. The similarity at 12 months between the pain and functional outcomes scores indicates that outcomes at the end of the recovery period are similar, and that there are key differences in the trajectory of recovery and risk of recurrence between approaches.

## References


[1] A. A. Momin and M. P. Steinmetz, “Evolution of minimally invasive lumbar spine surgery,” *World Neurosurgery*, vol. 140, pp. 622–626, 2020.

[2] L. A. Snyder, J. O’Toole, K. M. Eichholz, *et al*., “The technological development of minimally invasive spine surgery,” *BioMed Research International*, vol. 2014, Art. no. 293582, 2014.

[3] A. V. Khandge, S. B. Sharma, and J. S. Kim, “The evolution of transforaminal endoscopic spine surgery,” *World Neurosurgery*, vol. 145, pp. 643–656, 2021.

[4] S. Sharif and A. Afsar, “Learning curve and minimally invasive spine surgery,” *World Neurosurgery*, vol. 119, pp. 472–478, 2018.

[5] E. M. Valsamis, T. Chouari, C. O’Dowd-Booth, *et al*., “Learning curves in surgery: Variables, analysis and applications,” *Postgraduate Medical Journal*, vol. 94, pp. 525–530, 2018.

[6] F. A. Schmidt, T. Wong, S. Kirnaz, *et al*., “Development of a curriculum for minimally invasive spine surgery (MISS),” *Global Spine Journal*, vol. 10, no. 2 Suppl., pp. 122S–125S, 2020.

[7] M. Sarkar, J. Maalouly, S. Ruparel, *et al*., “Sacroiliac joint fusion: Fusion rates and clinical improvement using minimally invasive approach and intraoperative navigation and robotic guidance,” *Asian Spine Journal*, vol. 16, pp. 882–889, 2022.

[8] P. S. Page, S. G. Ammanuel, and D. T. Josiah, “Evaluation of endoscopic versus open lumbar discectomy: A multi-center retrospective review utilizing the American College of Surgeons’ National Surgical Quality Improvement Program (ACS-NSQIP) database,” *Cureus*, vol. 14, Art. no. e25202, 2022.

[9] W. X. Sun, W. Q. Huang, H. Y. Li, H. S. Wang, S. L. Guo, J. Dong, B. L. Chen, and Y. P. Lin, "Clinical efficacy of robotic spine surgery: An updated systematic review of 20 randomized controlled trials," *EFORT Open Reviews*, vol. 8, pp. 841–853, 2023.

[10] A. Ton, N. Hang, W. Liu, R. Liu, P. C. Hsieh, J. C. Wang, R. J. Hah, and R. K. Alluri, "Top 25 most-cited articles on robotic-assisted lumbar spine surgery," *International Journal of Spine Surgery*, vol. 18, pp. 37–46, 2024.

[11] P. Shahi, O. Maayan, D. Shinn, S. Dalal, J. Song, K. Araghi, D. Melissaridou, A. Vaishnav, K. Shafi, Y. Pompeu, *et al*., "Floor-mounted robotic pedicle screw placement in lumbar spine surgery: An analysis of 1050 screws," *Neurospine*, vol. 20, pp. 577–586, 2023.

[12] T. E. Komolafe, L. Zhou, W. Zhao, J. Guo, Z. Li, Z. Fan, B. F. Komolafe, W. Wei, and O. W. Samuel, "Advancing robot-guided techniques in lumbar spine surgery: A systematic review and meta-analysis," *Expert Review of Medical Devices*, vol. 21, pp. 765–779, 2024.

[13] J. Han, J. Guo, X. Ma, G. Zhang, S. Han, H. Zhang, H. Liu, M. Chen, and Y. Wang, "The cortical bone trajectory screw technique assisted by the Mazor Renaissance robotic system as a salvage strategy for failed lumbar spine surgery: Technical note and case series," *Journal of Pain Research*, vol. 16, pp. 2971–2980, 2023.

[14] H. Karimi, N. Taylor, J. Patel, L. Wiepert, R. I. Riesenburger, and J. Kryzanski, "Practice pattern variations in the use of neuromonitoring, image guidance, and robotics for lumbar pedicle screw placement based on a nationwide neurosurgery survey," *World Neurosurgery*, vol. 192, pp. e539–e546, 2024.

[15] M. J. Gouzoulis, A. E. Seddio, A. D. Winter, S. S. Jabbouri, J. R. Zhu, D. R. Rubio, A. G. Varthi, and J. N. Grauer, "Robotic-assisted versus navigation-assisted posterior lumbar fusion: A national database study," *Spine*, vol. 49, pp. 1483–1487, 2024.

[16] Y. Gezercan, G. Çavuş, A. I. Ökten, *et al*., "Single-stage posterolateral transpedicular approach with 360-degree stabilization and vertebrectomy in primary and metastatic tumors of the spine," *World Neurosurgery*, vol. 95, pp. 214–221, 2016.

[17] A. Phanphaisarn, J. Patumanond, J. Settakorn, *et al*., "Prevalence and survival patterns of patients with bone metastasis from common cancers in Thailand," *Asian Pacific Journal of Cancer Prevention*, vol. 17, pp. 4335–4340, 2016.

[18] S. Sohn, J. Kim, C. K. Chung, *et al*., "A nationwide epidemiological study of newly diagnosed spine metastasis in the adult Korean population," *The Spine Journal*, vol. 16, pp. 937–945, 2016.

[19] N. Fang, Z. Wang, J. Jiang, *et al*., "Nonsurgical therapy for lumbar spinal stenosis caused by ligamentum flavum hypertrophy: A review," *Medicine*, vol. 103, no. 27, Art. no. e38782, 2024.

[20] J. Patel, I. Osburn, A. Wanaselja, and R. Nobles, "Optimal treatment for lumbar spinal stenosis: An update," *Current Opinion in Anaesthesiology*, vol. 30, no. 5, pp. 598–603, 2017.

[21] K. N. Malik, C. Giberson, M. Ballard, N. Camp, and J. Chan, "Pain management interventions in lumbar spinal stenosis: A literature review," *Cureus*, published online Aug. 25, 2023.

[22] S. Jain, T. Deer, D. Sayed, *et al*., "Minimally invasive lumbar decompression: A review of indications, techniques, efficacy and safety," *Pain Management*, vol. 10, no. 5, pp. 331–348, 2020.

[23] H. Yuan and X. Yi, "Lumbar spinal stenosis and minimally invasive lumbar decompression: A narrative review," vol. 16, pp. 3707–3724, 2023.

[24] T. R. Deer, T. B. Chafin, S. J. Costandi, *et al*., "The MOTION study: Two-year results of a real-world randomized controlled trial of the mild® procedure for treatment of lumbar spinal stenosis," *Pain Practice*, vol. 24, no. 1, pp. 109–119, 2024.