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MISS innovations: Approaches, predictive outcomes and risk avoidance

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MISS innovations: Approaches, predictive outcomes and risk avoidance

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Table of contents

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Editorial: MISS innovations: Approaches, predictive outcomes, and risk avoidance

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minimally invasive spine surgery, degenerative disc disease, spinal cord tumors, spine endoscopy, lumbar interbody fusion, spinal cord injury

Editorial on the Research Topic
MISS innovations: Approaches, predictive outcomes, and risk avoidance

Introduction

Since its inception, minimally invasive spine surgery (MISS) has divided the community of spinal surgeons into firm supporters and outspoken opponents. After several decades, the field has accumulated a significant body of research confirming the effectiveness of MISS techniques (1). However, MISS has long been subjected to considerable criticism and comprehensive analysis. Though criticism towards the minimally invasive field continues, we must admit that the techniques employed have stood the test of time and continue to conquer more areas of neurosurgery.

After analyzing various experiences with spinal interventions and data from the current literature, four criteria for compliance of the intervention with the MISS category were identified: anatomical, technical, human, and instrumental. Modern MISS has ample opportunities for medical imaging of the pathology and pre-operative planning of approach trajectory, which allows us to limit iatrogenic damage to the surrounding tissues. These interventions are realized with the help of modern specialized equipment: x-ray-transparent tables, electron-optical converters, neuron navigators, illumination and optical magnification systems, power equipment, robotic systems, complex retractor systems, and specialized instrumentation allowing work at any operative depth (2).

MISS has a long learning curve and requires diverse staffing and educational approaches from various fields including orthopedics, vascular surgery, and radiology. The need for these skills accounts for the increasing role of cadaver and simulation courses in minimally invasive techniques. The variety of integrated systems and their installation can add complexity to MISS. The changing technology requires additional

education and training not only for the tools themselves, but also the most appropriate approach for a patient's unique anatomy while utilizing the tools. Additionally, the expanding selection of implants and materials, particularly bioactive materials, contribute to technique modification as well.

Results

In this issue of Frontiers of Surgery: "MISS innovations: Approaches, Predictive Outcomes, and Risk Avoidance," we are honored to present a collection of 14 publications that describe cutting-edge advances in MISS research and practice. These articles were selected through an open peer review process that brought together experts in spinal surgery, including 80 authors, 20 reviewers, and three editors.

In preparing this volume, the editorial team sought to highlight the ever-expanding field of applicational MISS techniques. Beginning as a separate set of techniques for the surgical treatment of degenerative diseases, MISS now tackles some of the most complex treatments, such as spinal oncology and severe spinal cord injury.

The first series of articles describes the results of minimally invasive techniques in the surgery of degenerative spinal lesions. The use of percutaneous transforaminal endoscopy under local anesthesia (3) demonstrates the technique's capabilities for patients with degenerative diseases of the lumbar spine to prevent nerve root damage and postoperative side effects.

In a cohort of patients with degenerative diseases of the cervical spine, Chen et al. (2022) studied the preliminary results of screwless cage placement. The satisfactory long-term clinical and radiological results can be summarized in future meta-studies (4).

Liang et al. (2022) investigated clinical outcomes and efficacy differences between paraspinal mini tubular lumbar decompression and minimally invasive transforaminal lumbar interbody fusion. The study considers the difference between the two concerning the treatment of degenerative grade I lumbar spondylolisthesis combined with spinal canal stenosis. The study shows that less extensive and costly treatment could be a viable primary surgical option for most patients.

Comparative studies are becoming increasingly important because of the variety of approaches to stabilizing intervention in patients with degenerative lumbar pathology. For example, Bokov et al. (2022) analyzed the potential effect of transforaminal lumbar interbody fusion (TLIF) vs. direct lateral interbody fusion (DLIF) on pedicle screw stability. The study demonstrated the advantage of DLIF technology in ensuring stability and reducing the frequency of revision interventions.

In contrast to the traditional transpedicular screw fixation technique, the cortical bone trajectory technique offers certain advantages. The reliability of screw placement along such a trajectory and prediction of screw loosening after single-level posterior lumbar interbody fusion using a nomogram was performed by Zhang et al. (2022).

While preparing this collection, we aimed to show an understanding of the significance and peculiarities throughout the lifetime of degenerative diseases of the spine in patients of older age. A systematic review, as seen in Techens et al. (2022) reflects the status of the increasingly popular lumbar cemented discoplasty technique. This technique can be used in elderly and high-risk polymorbid patients as a minimally invasive alternative to traditional spondylodesis.

In turn, a series of cases by Klimov et al. (2022) identified the main predictors of complications and adverse outcomes of minimally invasive surgical treatment in elderly patients with lumbar spine pathology.

The second block of articles is devoted to spinal neurooncology. Using minimally invasive approaches with tubular retractors can be used to optimize the surgical treatment of extramedullary tumors. For example, Kerimbayev et al. (2022) demonstrated the results of MISS for the treatment of dumbbell tumors with extra vertebral spread. The article shows a significant decrease in hospitalization time and postoperative pain syndrome compared to traditional open surgery. In addition, the long-term results of MISS techniques in the treatment of these types of tumors are studied by Pan et al. (2022).

To illustrate the possibilities of endoscopic techniques in spinal neurooncology surgery, the collection includes a case in Kravtsov et al. (2022) of successful percutaneous transforaminal endoscopic removal of neurinoma of the fifth lumbar spinal nerve using intraoperative neuromonitoring.

The neurooncology block concludes with a series by Yamada et al. (2022) emphasizing the importance of multimodal neurophysiological monitoring on the long-term outcomes of motor function after microsurgical resection for spinal cord tumors.

The block devoted to applying MISS technologies in patients with spinal cord injury presents a rare series, in Kravtsov et al. (2022) of three cases of lumbar and thoracic spinal bullet wounds sustained from firearms and traumatic weapons. Percutaneous endoscopic techniques were successfully used for bullet extraction from the spinal canal.

The collection concludes with two unique papers: a rare case of Crowned Dens Syndrome treatment with occipital-cervical fixation technology by Haas et al. (2022) and a literature review and the results of robotic technology in combination with MISS [Minimally Invasive Assisted Robotic Spine Surgery (MARSS)] seen in Pérez de la Torre et al. (2022).

Summary

As MISS continues to face new challenges, the ever-expanding possibility of this technology requires further efficacy studies in new fields of spinal surgery. The current trend of modern spine surgery is the use of minimally invasive approaches, specialized retractors, and endoscopes combined with imaging and navigation systems (2). MISS will continue developing in new areas previously available only to traditional open surgery. We are proud to present our compendium reflecting these advances in spine surgery, delivered in the least invasive manner and accompanied by the best clinical outcomes and minimal surgical complications.

Author contributions

VB, DS, and MG drafted and revised the manuscript. VB, DS, and MG initiated the manuscript and guided with editorial comments after review. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

1. Patel PD, Canseco JA, Houlihan N, Gabay A, Grasso G, Vaccaro AR. Overview of minimally invasive spine surgery. *World Neurosurg.* (2020) 142:43–56. doi: 10.1016/j.wneu.2020.06.043

2. Byvaltsev VA, Kalinin AA, Konovalov NA. Minimal'no invazivnaia khirurgiia pozvonochnika: étapy razvitiia [minimally invasive spinal surgery: stages of development]. *Zh Vopr Neirokhir Im N N Burdenko.* (2019) 83(5):92–100 (Russian). doi: 10.17116/neiro20198305192

3. Kerimbayev T, Kenzhegulov Y, Tuigynov Z, Aleinikov V, Urunbayev Y, Makhambetov Y, et al. Transforaminal endoscopic discectomy under general and local anesthesia: a single-center study. *Front Surg.* (2022) 9:873954. doi: 10.3389/fsurg.2022.873954

4. Chen X, Sial A, Stewart C, Castillo JV, Diwan A. Stand-alone anterior cervical decompression and fusion surgery a cohort study evaluating a shaped cage without plates or screws. *Front Surg.* (2022) 9:873954. doi: 10.3389/fsurg.2022.934018

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Minimally Invasive Posterolateral Approach for Surgical Resection of Dumbbell Tumors of the Lumbar Spine

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Minimally invasive spine surgery (MISS) has many advantages over traditional open surgical procedures that can be conducted for the therapy of different diseases of the spine. MISS provide many prospective advantages such as, for example, small incisions, less damage to soft tissues, early activation of patients, and a shorter postoperative hospital stay. The aim of the study was to evaluate institutional experience with Dumbbell tumors and metastatic lesions of the lumbar spine and compare it with traditional open surgical resection of this type of tumors. Fourteen patients underwent the surgery with minimally invasive posterolateral approach in experimental group, and 10 patients of the control group were operated using the traditional open surgery procedure at the Department of spinal neurosurgery and pathology of peripheral nervous system of JSC "National Center for Neurosurgery." The intraoperative neuro monitoring system (ISIS IOM System Compact, Inomed, Germany) was used in both groups. Sensory and motor evoked potentials were intraoperatively recorded. The present study was approved by the local Ethics Committee of the National Center for Neurosurgery. Patients signed informed consent before the surgical procedure. The experimental group included 14 patients, that underwent the surgery during the period from January 2020 till March 2021. And the control group included 10 patients that was operated from January 2018 to December 2019. The results of the treatment in both groups were assessed according to the generally accepted visual analog scale (VAS) and the Oswestry scales before, on the third day, and 3 months after the surgery. In experimental group, average reduction of the pain syndrome of 3.36 points (from 3 to 0 points) was observed in patients postoperatively according to the VAS 3 days, and of 4.0 points (from 2 to 0 points) 3 months after surgical procedures. Improvement by 23.86% (36–16%) was also observed using the Oswestry Disease Index (ODI) 3 days after the surgery, and then reduced to 21.00% (16–34%) in average in 3 months. All patients were revived 3 h after transfer to the specialist department. The average stay in the hospital was 6.5 (9–4) days in both groups. In control group, average reduction of the pain syndrome of 2.60 points (from 4 to 1 points) was

observed postoperatively according to the VAS 3 days after the operation, and of 3.9 points (from 2 to 0 points) 3 months after the surgery. The ODI of patients was also improved by an average of 35.40% (50–20%) 3 days after the surgical procedure, and reduced to 24.20% (16–32%) in average 3 months after the surgery.

Keywords: lumbar spine, dumbbell tumor, minimally invasive, posterolateral approach, resection

INTRODUCTION

Minimally invasive spine surgery (MISS) is an alternative to traditional open surgical procedures performed for the treatment of various diseases of the spine, such as osteochondrosis, herniated disc, scoliosis, spinal stenosis, and tumors. MISS offer many potential benefits, such as small incisions, less damage to soft tissues (ligaments, muscles), early activation of patients, and a shorter postoperative hospital stay (1, 2). Nowadays, there is a possibility (if necessary) to stabilize the functional spinal unit (FSU) using the percutaneous technique of introducing transpedicular screws.

Among spinal neoplasms, the incidence of dumbbell tumors is 13–14% of those occupying the perforaminal location, while in 41% of cases, tumors are observed in the cervical spine. The traditional surgical approach for the removal of such type of tumors involves an extended skin incision with dissection of soft tissues and extensive skeletonization of the muscle layer; resection of the arches and facet joints of the vertebrae. This, in turn, potentially cause instability in the involved FSU.

In 1941, Eden proposed a classification in which tumors are systematized depending on their topographic and anatomical interrelation with the nerve and bone structures of the spine. However, it does not provide an answer regarding the size of neoplasms. According to the literature, the most common type of tumors is type III tumors with extradural and paravertebral components according to the Eden's classification (**Figure 1**) (3). Metastatic lesions of the spinal cord and the spine can also occur in the perforaminal location—a common complication of cancer disease. Damage of the spine and roots of the spinal cord can significantly reduce the quality of life of patients, potentially causing persistent pain (4). Due to the early detection and an increase in the life expectancy of patients with malignant tumors, the number of patients at risk of developing metastases is increasing every year (5, 6). According to the statistics, the spine is the third most frequent region of cancer cell metastasis after the lungs and liver. And it is expected, that nearly 70% of cancer patients will have metastases to the spine. In the case of symptomatic lesions, the majority of metastases (60–70%) are found in the thoracic region, while the remaining 20% are in the lumbar region and 10% in the cervical spine. More than 50% of patients with spinal metastases have more than one lesion level (7, 8).

The goal of surgical intervention for spinal metastases is palliative care in the form of pain reduction and improvement of the quality of life in patients with pain syndrome. In some cases, if necessary, stabilization of the spinal motion segments is performed. Moreover, one of the goals of the surgery is the collection of biopsy material for subsequent histological and immunohistochemical studies. In order to reduce postoperative complications and speed up postoperative recovery of patients, minimally invasive approaches may be the best technique of surgical intervention. Satisfactory decompression and minor surgical aggression are critical for patients with concomitant conditions and untreated accompanying decompensated disease that prevents comprehensive surgery (9). Recent advances in microsurgical techniques have led to the development of minimally invasive approaches for the treatment of primary and metastatic spinal lesions. This, in turn, results in reduced postoperative pain, shorter overall hospital stay, reduced blood

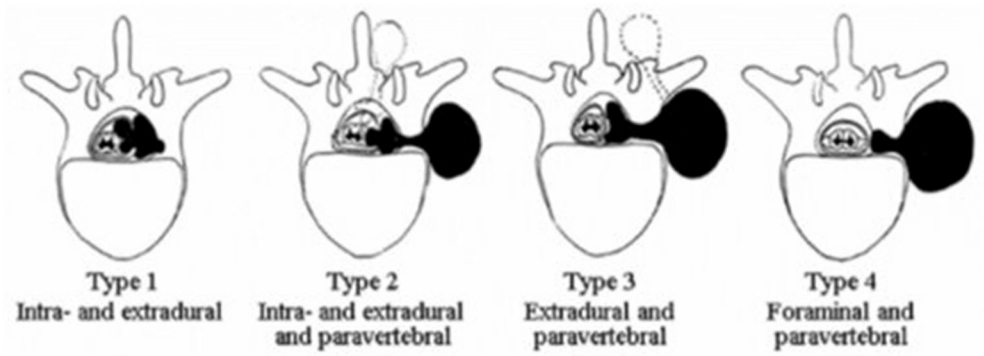


FIGURE 1 | Eden's classification of spinal dumbbell tumors, from left to right: type I–rumors with intra- and extradural components; type II–with intra-, extradural, and paravertebral components, type III–with extradural and paravertebral components, type IV–with foraminal and paravertebral components.

TABLE 1 | Results of performed surgery on 14 patients (Experimental group).

Gender/ age (y)	The level of lumbar spine lesions	Type of a tumor according to Eden's classification	VAS before the surgery	Oswestry before the surgery	Histology	VAS after the surgery	VAS after 3 month surgery	Ostwery after the surgery	Ostwery after 3 month surgery	The number of days spent in stasis unit	Required instrumentation (fusion)	Blood loss	Operation time
1. Fem/33	L2–L3 left side	3	3	38	Schwannoma	0	0	18	18	5	No	30	115
2.Fem/45	L4–L5 right side	3	5	50	Schwannoma	2	2	24	20	7	No	35	80
3.Fem/74	L3–L4 right side	4	7	74	Mts	3	2	34	34	9	No	110	150
4.Male/51	L1–L2 left side	4	4	42	Schwannoma	0	0	24	18	6	No	45	90
5.Male/60	L2–L3 left side	4	3	40	Schwannoma	1	1	18	16	5	No	50	85
6.Fem/65	L1–L2 left side	4	6	68	Mts	2	1	36	28	7	No	30	125
7.Fem/45	L3–L4 right side	3	4	48	Schwannoma	1	1	22	18	5	No	35	100
8.Male/42	L4–L5 left side	4	4	50	Schwannoma	1	0	22	18	6	No	50	120
9.Fem/32	L2–L3 right side	4	2	44	Schwannoma	0	0	16	16	4	No	35	105
10.Male/69	L1–L2 right side	4	6	64	Mts	2	1	32	28	8	No	65	100
11.Fem/50	L2–L3 right side	3	4	46	Schwannoma	1	1	20	20	7	No	50	140
12.Male/41	L2–L3 right side	3	3	40	Schwannoma	0	0	18	18	7	No	30	90
13.Male/62	L3–L4 left side	4	6	66	Schwannoma	1	0	26	22	8	No	35	80
14.Fem/54	L4–L5 left side	4	4	62	Schwannoma	0	0	24	20	7	No	30	95

loss during surgery, improved neurological status, and earlier initiation of adjuvant therapy (10, 11). These benefits are particularly crucial for maintaining and improving the quality of life of cancer patients with a short life expectancy (12, 13). The MISS methodology aims to perform: a minimally invasive posterolateral tubular access to remove the tumor and decompress the spinal cord, reducing intraoperative blood loss and postoperative pain.

Yet, there is some criticism of this technique in the form of difficulties in achieving sufficient decompression of the spinal cord. This is the result of the mistaken belief that the greater the surgical exposure, the better the results are achieved. On the contrary, in fact, MISS techniques provide facilitated access to the spinal canal and complete decompression of the spinal cord and its roots (14, 15).

MATERIALS AND METHODS

The present study is a consistent retrospective single-center case control series study. Cases of dumbbell tumors and metastatic lesions of the lumbar spine were included in this study. In the experimental group, 14 patients underwent surgery with minimally invasive posterolateral approach (**Table 1**), and 10 patients in control group were operated using the traditional open surgery technique (**Table 2**) at the Department of spinal neurosurgery and pathology of peripheral nervous system of JSC "National Center for Neurosurgery." Intraoperative neuro-monitoring system (ISIS IOM System Compact, Inomed, Germany) was used in both groups. Sensory and motor evoked potentials were intraoperatively recorded. The present study was approved by the local Ethics Committee of the National Center for Neurosurgery. Patients signed informed consent before surgical procedure. Experimental group included 14 patients, that underwent the surgery during the period from January 2020 till March 2021. And the control group included 10 patients that was operated from January 2018 to December 2019. Two groups was consecutive case series. Data on the experimental group are highlighted in **Table 1**, and data on the control group are presented in **Table 2**. Diagnosis and preoperative assessment were performed using magnetic resonance imaging (MRI) with contrast enhancement of the lumbar spine. Patients with tumor sizes >8.0 cm in the largest diameter according to MRI data were excluded from this study in two groups. Evaluation of the stability of FSU was performed using functional

TABLE 2 | Results of performed surgery on 10 patients (Control group).

Gender/ age (y)	The level of lumbar spine lesions	Type of a tumor according to Eden's classification	VAS before the surgery	Oswestry before the surgery	Histology	VAS after the surgery	VAS after 3 month surgery	Oswestry after the surgery	Oswestry after 3 month surgery	The number of days spent in stasis unit	Requared instrumentaion (fusion)	Blood loss	Operation time
1.Male/25	L3–L4 left side	3	4	40	Schwannoma	1	0	20	16	9	No	150	90
2.Male/62	L3–L4 left side	4	6	66	Schwannoma	2	0	44	32	10	Yes	170	120
3.Fem/35	L4–L5 right side	3	4	64	Schwannoma	2	1	50	30	10	No	120	90
4.Fem /50	L2–L3 right side	4	5	46	Schwannoma	2	0	36	22	9	No	80	100
5.Male/40	L1–L2 left side	3	4	40	Schwannoma	1	0	20	16	7	No	70	120
6.Male/60	L2–L3 right side	4	6	50	Mts	2	1	36	30	6	No	80	80
7.Fem/43	L4–L5 right side	4	5	56	Schwannoma	2	1	24	20	7	No	100	70
8.Fem /48	L3–L4 left side	3	4	54	Schwannoma	3	1	40	22	10	No	90	90
9.Male/40	L1–L2 left side	4	4	40	Schwannoma	2	1	36	22	8	No	70	100
10. Male/60	L1–L2 right side	3	4	60	Schwannoma	4	2	48	32	12	No	110	90

X-ray images. The results of the treatment in both groups were assessed according to the generally accepted the VAS and the ODI scales before the surgery, on the third day, and 3 months after the surgerical procedures. Before the surgical operation, all patients underwent hormonal preoperative preparation with intravenous dexamethasone according to the scheme of 16 mg per day for 2 days. All patients were administered non-steroidal anti-inflammatory drug after the surgical procedure 8–16 mg intramuscularly daily depending on the VAS of a patient. We used standard surgical technique that is described below in the chapter "Description of the surgical procedure" to reduce inter- or intra-operation variations, ensure the quality, and maintain consistency between cases. The follow-up period after the surgery of all patients was 3–12 months (6.5 months on the average) with contrast MRI of the lumbar spine 3 days and 3 months after surgical procedures.

Description of the Surgical Procedure

Intervention Details

All surgical manipulations on removing tumors and metastatic lesions were performed *via* minimally invasive posterolateral access using the Mast Quadrant Tubular Retractor System (Medtronic Sofamor Danek, Memphis, TN, USA). All patients underwent the surgery with IONM with recording of sensory and motor signals from the lower limbs. Patients were administered general anesthesia before the surgical procedure, and then laid on a multifunctional operating table, in a supine position with pelvic rollers under the shoulders and with the arms brought forward. Intraoperative fluoroscopy was used to determine the level of surgical intervention. All 24 surgical procedures in two groups (the experimental group and the control group) were performed by three senior neurosurgeons, with the experience more than 15 years in the spine surgery. A minimally invasive posterolateral tubular approach was performed through a linear skin incision about 2.0 cm long (1.5–2.5 cm), extending from the supraspinous line (paraspinally) to the width of the paraspinal muscles (5.0–8.0 cm) at a sufficient angle to expose the ipsolateral extraforaminal space of the affected region. The subcutaneous fatty tissue and muscle layer were "dilated" using a tubular system, under fluoroscopic control (straight and lateral spondylograms). The handle of the tubular dilator was rigidly attached to the operating table using a holder. Further imaging was performed under an operating microscope (HS 5–1,000, Haag-Streit Surgical, Germany) at up to 24-x magnification. The space between the transverse processes of the adjacent vertebral segments was found and partially resected with Kerrison-type 2.0 bone excisors, when it was necessary. The extraforaminal components of the tumor were isolated using microinstrumentation, and when it was necessary, removal was performed using an ultrasound aspirator. The exiting nerve root was completely exposed, and the dura mater was identified. During the surgical operation the nerve root was protected using a "holder." The foraminal opening was completely cleared of the tumor and decompression was performed. Tumor tissue was sent for the histological analysis. Thorough hemostasis was performed at all stages of the surgery. Fascia and aponeurosis were sutured in layers with interrupted sutures. The tubular retractor was removed. Then, a cosmetic, atraumatic, continuous suture was applied to the skin. A drainage tube was installed into the wound cavity when it was necessary. **Figures 2–6** illustrate case

examples of the surgical removal of a tumor with every stage of the surgery.

Statistical Analysis of Variables Between Two Groups Is Presented in Table 3

*p-values had been calculated using chi-square test or Fisher's exact test for categorical variables, while Mann-Whitney U-test had been used for numeric variables. Comparison of variables between two groups.

RESULTS

All 14 patients in the experimental group underwent single-stage minimally invasive posterolateral approach with the follow-up period from 3 to 12 months (6.5 months on the average). Other characteristics of patients related to gender, age, diagnosis, and comorbidities are highlighted in **Table 1**. According to Eden's classification, 5 (35.7%) patients had type III of spinal dumbbell tumor, and 9 (64.3%) patients had type IV of the tumor. The most patients (5 patients, 35.7%) of the experimental group underwent surgical resection of L2–L3 vertebrae. Total tumor removal was achieved in 12 patients (85.7%), and subtotal tumor removal was performed in 2 patients (14.3%) with cases of comprehensive metastatic lesions. In the experimental group, radiological assessment of the stability of the involved FSU was performed postoperatively (X-ray with functional tests of the lumbar spine), and stabilization was not required in this group. The surgical operation lasted 80–150 min (mean−105.36 min) with blood loss of 30–110 ml (mean−45.0 ml). Histological analysis revealed schwannomas in 11 (78.6%) patients, while undifferentiated carcinoma metastases was observed in 3 (21.4%) patients. No recurrence was observed in schwannomas during the follow-up period. The main preoperative indicators such as the VAS and the ODI scores in both groups were 4.60 and 4.36, 51.60 and 52.29% on average, respectively. There were no significant intraoperative or postoperative complications in our series of all 24 patients in both groups. The neurological status of all patients in the postoperative period remained without worsening of sensory and motor responses in the extremities compared to the preoperative state (as indicated by IONM). It could be due to the adequate visualization of the nerve structures and the use of IONM. In experimental group, the average reduction of the pain syndrome of 3.36 points (from 3 to 0 points) was observed according to the VAS 3 days in the postoperative period, and of 4.0 points (from 2 to 0 points) 3 month after the surgical operation. The same picture was also observed using the ODI on the third day after the surgery [23.86% on the average (36–16%)]. Moreover, this score reduced to 21.00% (16–34%) on the average in 3 months. All patients were revived 3 h after transfer to the specialist department. The average hospital stay was 6.5 (9–4) days on the average. Regarding the control group, reduction of the pain syndrome was also observed in patients postoperatively: the VAS was 2.60 points (from 4 to 1 points) on

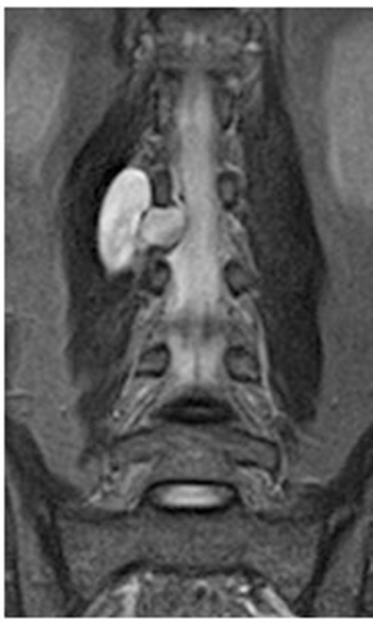


FIGURE 2 | Preoperative contrast-enhanced MRI of the lumbar spine.

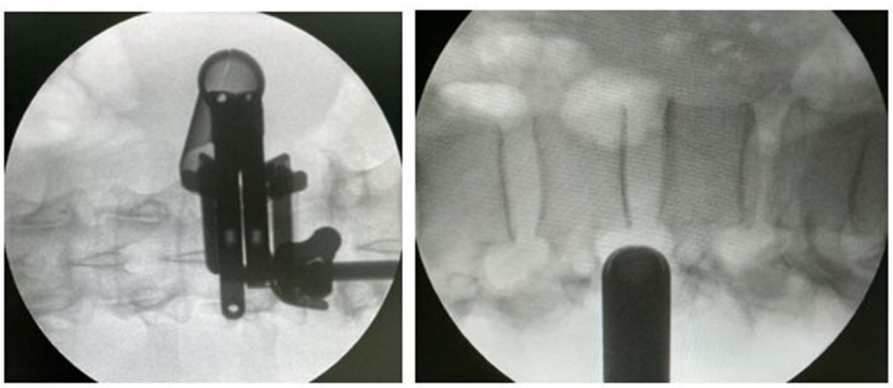


FIGURE 3 | Direct and lateral X-ray control during the surgery.

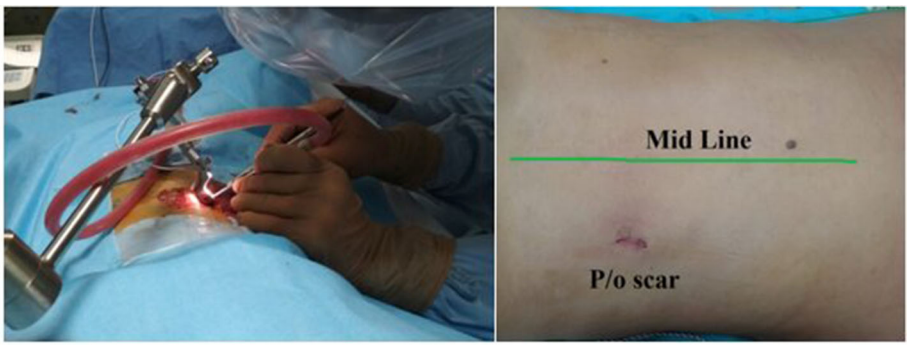


FIGURE 4 | Left side–Intraoperative picture; right side–postoperative scar (2 cm).

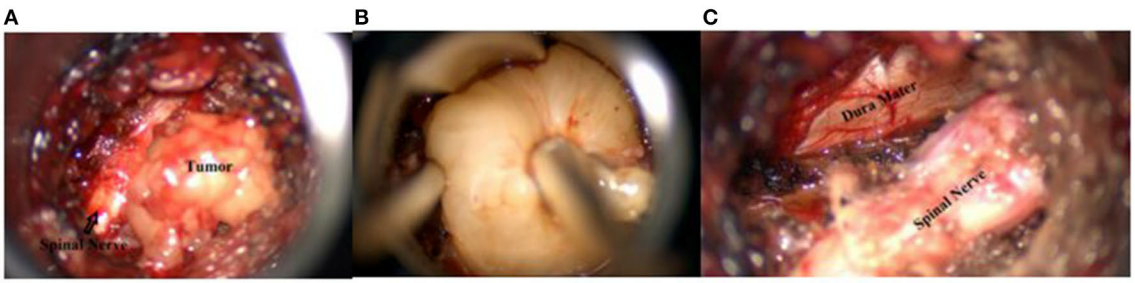


FIGURE 5 | (A) The rumor and compressed emerging nerve root (picture obtained from the operating microscope); **(B)** Intraoperative photograph: removal of the tumor; **(C)** After the removal of the tumor, the dura mater and root are visualized (photograph from the operating microscope).

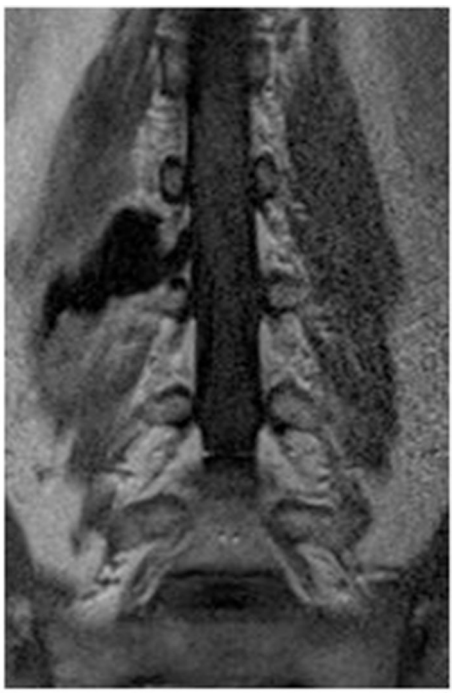


FIGURE 6 | MRI of the lumbar spine with contrast after the surgery.

the average 3 days after the surgical procedure, and 3.9 points (from 2 to 0 points) 3 months after the surgery. Enhancement was also observed in ODI [35.40% (50–20%) on average] in 3 days, and reduced to 24.20% (16–32%) on the average 3 months after the operation. The results of the performed surgery in control group are shown in **Table 2**.

DISCUSSION

This study produced promising findings concerning minimally invasive posterolateral approach for tumors of the spinal cord and its roots, comparing to the traditional laminectomy with resection of the arches and facet joints of the vertebrae. As an example, in one of the cases of the study in a control group, the surgical procedure on stabilization of the spinal motion segment on the level of L3–L4 vertebrae was performed in a patient. The patient had the pain syndrome in the lumbar region as a result of instability that was confirmed on control radiographs with functional tests. This procedure was carried out to stabilize the functional spinal unit using percutaneous technique of introducing transpedicular screws. As a result of the stabilization, the pain syndrome totally regressed during 3 months postoperatively.

On the contrary, patients of the experimental group did not require additional stabilizing surgery, that contribute to the

TABLE 3 | Comparison of variables between two groups.

Variables	Control ($n = 10$)	MISS ($n = 14$)	p-value
Gender, Male (%)	6 (60.0)	6 (42.9)	0.68
Age (years)			
Median (IQR)	45.5 (40–57.5)	50.5 (42.8–61.5)	0.32
Mean (SD)	46.30 (12.07)	51.64 (12.99)	
The level of lumbar spine lesions (%)			0.84
L1–L2	3 (30.0)	3 (21.4)	
L2–L3	2 (20.0)	5 (35.7)	
L3–L4	3 (30.0)	3 (21.4)	
L4–L5	2 (20.0)	3 (21.4)	
VAS before the surgery			
Median (IQR)	4 (4–5)	4 (3.3–5.8)	0.64
Mean (SD)	4.60 (0.84)	4.36 (1.45)	
Oswestry before the surgery			
Median (IQR)	52 (41.5–59)	49 (42.5–63.5)	0.88
Mean (SD)	51.60 (9.97)	52.29 (12.05)	
Histology, Schwannoma (%)	9 (90.0)	11 (78.6)	0.85
VAS after the surgery			
Median (IQR)	2 (2–2)	1 (0–1.8)	0.01
Mean (SD)	2.10 (0.88)	1.00 (0.96)	
VAS after 3 month surgery			
Median (IQR)	1 (0–1)	0.5 (0–1)	0.85
Mean (SD)	0.70 (0.67)	0.64 (0.74)	
Ostwery after the surgery			
Median (IQR)	36 (27–43)	23 (18.5–25.5)	<0.01
Mean (SD)	35.40 (10.92)	23.86 (6.25)	
Ostwery after 3 month surgery			
Median (IQR)	22 (20.5–30)	19 (18–21.5)	0.19
Mean (SD)	24.20 (6.29)	21.00 (5.31)	
The number of days spent in stasis unit			
Median (IQR)	9 (7.3–10)	7 (5.3–7)	<0.01
Mean (SD)	8.80 (1.81)	6.50 (1.40)	
Required instrumentation (fusion), Yes (%)	1 (10.0)	0 (0.0)	0.86
Blood loss			
Median (IQR)	95 (80–117.5)	35 (31.3–50)	<0.001
Mean (SD)	104.00 (34.06)	45.00 (21.48)	
Operation time			
Median (IQR)	90 (90–100)	100 (90–118.8)	0.22
Mean (SD)	95.00 (15.81)	105.36 (21.88)	

TABLE 4 | Comparison ODI.

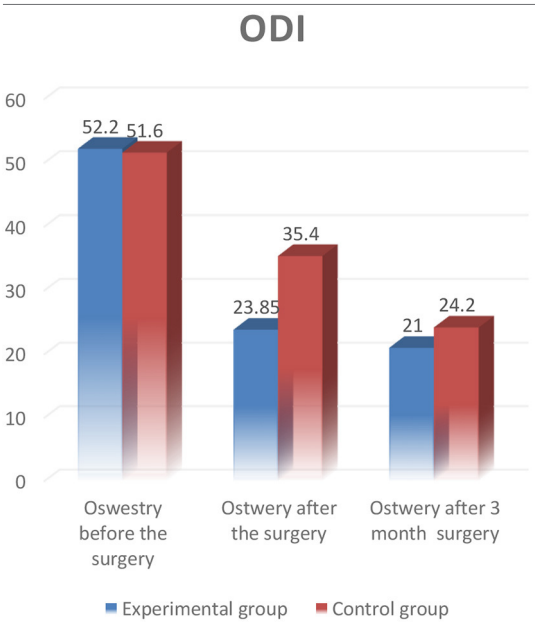
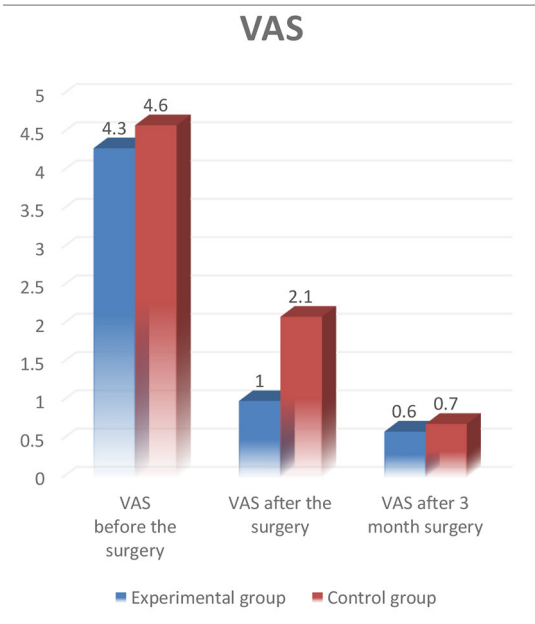


TABLE 5 | Comparison VAS.



preservation of the arch and the facet joint in the stability of the spinal motion segment postoperatively in patients with this kind of spinal cord tumors.

There is a conviction that surgical resection of dumbbell tumors of the spinal cord and its roots is always challenging. Yet, based on our own experience, we can still claim that minimally invasive posterolateral approach is a worthy alternative to the traditional surgical procedures in resection of such types of tumors in the spinal cord and its roots. For example, nowadays, minimally invasive decompression and stabilization methods are widely used by spinal surgeons and linked to more optimistic clinical results due to reduced paravertebral tissue injury, minimum postoperative pain syndrome, and shorter patient's recovery time after the operation (1, 2). The minimally invasive posterolateral approach for tumors of the spinal cord and its roots has many advantages in contrast to the traditional laminectomy. Firstly, there is no traction on nerve structures, which in turn contribute to prevention of post-operative neurological

complications. Secondly, it facilitates to preservation of the ligamentary apparatus further maintaining movement ability in the functional segment. Moreover, the most important benefit of the MISS is the complete removal of the spinal cord tumor. Lastly, minimally invasive posterolateral approach promotes early postoperative rehabilitation of patients. As a result, patients can have the possibility to take an upright posture the same day after the surgical procedure without additional external immobilization devices. This is confirmed in the present study by comparison of both groups of patients (**Table 3**). In the MISS group, more rapid improvement was observed in the ODI when assessed on the 3rd day after the surgery (23.86 points on the average) comparing to the data in the control group that was 36.40 points on the average. Nevertheless, the leveling of the difference of this indicator by the third month was also noted on the average 24.20 points in the MISS group, and 21.00 points in the control group (**Table 4**).

However, the difficulties of using MISS to decompress sufficiently the spinal cord, in spinal cord tumors still remain controversial. On the contrary, MISS techniques provide easy access to the spinal cord and its roots, as well as their complete decompression, if necessary. In comparison to the traditional laminectomy allows to decrease the volume of blood loss by a patient, and to reduce significantly the pain syndrome after the surgery according to the VAS.

In our experimental group, the decrease in the VAS was 3.36 units after the surgical procedure, and 4.0 units 3 months after the surgery comparing to the control group, where the decrease in the VAS after the operation was 2.6 and 3.9 units on the average 3 months after the surgical procedure. Based on the obtained data, we can expect a faster reduction in the pain syndrome in patients when using the minimally invasive posterolateral approach, by 1.0 point on the average within 3 days after the surgery (**Table 5**).

In addition, the somatic status of patients was considerably improved. Nevertheless, further prospective research including larger amount of patients with longer follow-up period is of a strong need in order to compare various results representing the effectiveness and lack of side effects of microsurgical techniques compared to traditional open surgical procedures.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the National Center for Neurosurgery, November 2019. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

TK: conceptualization. ZT: data collection. TK, VA, YU, and NA: surgical procedures. MO, NA, and YK: postoperative observation of patients. TK, ZT, and VA: writing draft. DB, MS, and SA: review and editing of manuscript. All authors contributed to the article and approved the submitted version.

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REFERENCES

1. Moses ZB, Barzilai O, O'Toole JE. Benign intradural and paraspinal nerve sheath tumors: advanced surgical techniques. *Neurosurg Clin N Am.* (2020) 31:221–9. doi: 10.1016/j.nec.2019.11.002
2. Byvaltsev VA, Kalinin AA, Giers MB, Shepelev VV, Pestryakov YY, Biryuchkov MY. Comparison of MRI visualization following minimally invasive and open TLIF: a retrospective single-center study. *Diagnostics*. (2021) 11:906. doi: 10.3390/diagnostics11050906
3. Nittner K. Spinal meningiomas, neurinomas and neurofibromas, and hourglass tumors. *Handb Clin Neurol.* (1976) 20:177–322.
4. Ogden AT, Schwartz TH, McCormick PC. Spinal cord tumors in adults. In: Winn HR, editor. *Youmans Neurological Surgery*. Philadelphia, PA: Elsevier (2011). p. 3131–43. doi: 10.1016/B978-1-4160-5316-3.00312-9
5. Sridhar K, Ramamurthi R, Vasudevan MC, Ramamurthi B. Giant invasive spinal schwannomas: definition and surgical management. *J Neurosurg.* (2001) 94:210–5. doi: 10.3171/spi.2001.94.2.0210
6. Miscusi M, Forcato S, Raco A. Minimally invasive surgery for treatment of patients with advanced cancer and thoraco-lumbar spine metastases. *Neurooncology*. (2016) 18:421–34. doi: 10.5772/63244
7. Ibrahim A, Crockard A, Antonietti P, Boriani S, Bünger C, Gasbarrini A, et al. Does spinal surgery improve the quality of life for those with extradural (spinal) osseous metastases? An international multicenter prospective observational study of 223 patients. Invited submission from the joint section meeting on disorders of the spine and peripheral nerves. *J Neurosurg Spine.* (2008) 8:271–8. doi: 10.3171/SPI/2008/8/3/271
8. Ofluoglu O. Minimally invasive management of spinal metastases. *Orthop Clin North Am.* (2009) 40:155–68. doi: 10.1016/j.ocl.2008.09.006
9. Bhatt AD, Schuler JC, Boakye M, Woo SY. Current and emerging concepatients in noninvasive and minimally invasive management of spine metastasis. *Cancer Treat Rev.* (2013) 39:142–52. doi: 10.1016/j.ctrv.2012.08.002

10. Zairi F, Troux C, Sunna T, Karnoub MA, Boubez G, Shedid D. Minimally invasive resection of large dumbbell tumors. *Clin Neurol Neurosurg.* (2018) 18:30100–8. doi: 10.1016/j.clineuro.2018.03.005
11. Balak N. Unilateral partial hemilaminectomy in the removal of a large spinal ependymoma. *Spine J.* (2008) 8:1030–6. doi: 10.1016/j.spinee.2007.07.001
12. Mende KC, Krätzig T, Mohme M, Westphal M, Eicker SO. Keyhole approaches to intradural pathologies. *Neurosurg Focus.* (2017) 43:E5. doi: 10.3171/2017.5.FOCUS17198
13. Ito K, Aoyama T, Kuroiwa M, Horiuchi T, Hongo K. Surgical strategy and results of treatment for dumbbell-shaped spinal neurinoma with a posterior approach. *Br J Neurosurg.* (2014) 28:324–9. doi: 10.3109/02688697.2013.835372
14. Xu J, Liu CH, Lin Y, Luo FQ. Microscopic minimally invasive keyhole technique for surgical resection of spinal dumbbell tumors. *World Neurosurg.* (2017) 109:e110–7. doi: 10.1016/j.wneu.2017.09.114
15. Liu T, Liu H, Zhang JN, Zhu T. Surgical strategy for spinal dumbbell tumors: a new classification and surgical outcomes. *Spine.* (2017) 42:E748–54. doi: 10.1097/BRS.0000000000001945

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers in Surgery

CASE REPORT
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Case Report: Full-Endoscopic Surgery for Bullet Wounds of the Spine: A Report of Three Cases

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Objectives: To determine the feasibility and evaluate effectiveness of full-endoscopic surgery in gunshot wound of the spine.

Methods: Three clinical cases of lumbar and thoracic spine bullet wounds made by firearms and traumatic weapons are described. Percutaneous endoscopic surgery was performed to extract bullet from the spinal canal. The results are compared to the data from literature.

Results: Percutaneous endoscopic approach to spinal canal with a possibility to extract a bullet, decompression of nerve roots, defect closure of the dura mater is demonstrated.

Conclusion: Good clinical outcomes allows to recommend percutaneous endoscopic surgery to manage similar lumbar and thoracic spine bullet wounds at the tertiary care level.

Keywords: gunshot wound, injury, lumbar spine, thoracic spine, full-endoscopic surgery

INTRODUCTION

The potential of full-endoscopic surgery has greatly improved thanks to advanced video transmission quality, upgrades of endoscopes and related instruments and the development of new surgical techniques and approaches. It all resulted in expanding indications for this type of treatment (1, 27). However, degenerative-dystrophic diseases of the spine still remain the main pathology where percutaneous endoscopic interventions are largely used (2). Also, a beneficial effect of the described method was noticed in revision surgery after metal osteosynthesis (3), in non-specific spondylodiscitis (4) and spinal tumors (5, 6).

This paper assesses preliminary results of percutaneous video endoscopy for gunshot bullet wounds in the lumbar spine; presents capabilities of surgical technique for extraction of a

foreign body from the spinal canal and intervertebral disc. Treatment of traumatic spinal injuries logically originates from percutaneous video endoscopic spinal surgery.

CLINICAL CASE NO. 1

The wounded person, a 24-year-old man, was admitted to the neurosurgery clinic the next day after he had received a gunshot blind wound in the lumbar region. The patient complained of weakness in the feet, numbness on the back surface of both legs and perineum, impaired sensation of bladder filling. These effects occurred immediately after the injury. During the day, weakness in the right foot increased. Upon admission, the examining physician saw an inlet of the gunshot wound, 10 × 5 mm in size, located in the lumbar region, 6 cm left to the spinous processes line. In the history, there was no intense bleeding or fluid leakage from the wound inlet. The general condition of the patient remained stable, urination passed through the urinary catheter, with normal urine output and normal color of the urine. Neurological status: low flaccid distal paraparesis up to 3 points, bilateral absence of Achilles reflexes, anesthesia in S1-S5 dermatomes, urinary retention.

Computed tomography confirmed a left-sided wound inlet and channel with an oblique trajectory that ended blindly in the spinal canal close to the right L5-S1 intervertebral joint, where CT picture showed a foreign metal body—a bullet. There were no bone injuries in the spine or impaired large vessels and internal organs in the abdominal cavity, retroperitoneal space and small pelvis. Apart from the bullet, there were no other signs of neural structures compression (**Figure 1A**).

Results of the examination proved that neurological disorders were likely to be caused by direct trauma to the *cauda equina* and persistent roots compression by the injuring body. The purposes of surgical intervention were extracting the bullet and revising structures of the spinal canal with the help of percutaneous video endoscopy. Should it appear impossible to achieve those purposes, it was planned to convert to open access.

Surgery

After general anesthesia induction the patient was prone positioned; under fluoroscopic guidance in AP view, a puncture access with an 18G needle was made to the arch of the L5 vertebra 1 cm right to the spinous processes line. The access trajectory did not coincide with the gunshot wound projection. A wire guide was inserted, and a linear cut up to 1 cm long was made. Along the guide, with the help of tubular expanders, a working tube with an outer diameter of 8 mm was inserted through the cut. A SpineTip endoscope (Karl Storz, Germany) was inserted into the working tube (**Figure 1B**).

Further manipulations were controlled by video endoscopy backed by continuous irrigation with saline sodium chloride solution through a special endoscopic channel. The lower edge of the L5 vertebra arch was skeletonized and partially resected with a diamond burr in order to increase the interlaminar space. The revision showed a distal end of the bullet within the defect of the yellow ligament. With the help of video endoscopy, the working tube axis was aligned with the bullet axis. After partial flavotomy, the bullet was captured with forceps and removed through the lumen of the working port together with the endoscope. Revision of the epidural space showed defects of the dura mater, endoscopic analysis proved anatomical integrity of the roots. The epidural space was revised above and below the injury area. Defects in the dura mater were covered with Fibrin-collagen patch TachoComb® introduced through the working port. Each stage of the surgery is shown in **Figures 1C,D** and **Supplementary Video 1**.

A temporary stop of irrigation helped to detect endoscopic signs of unstable cerebrospinal fluid stasis. The endoscope and working port were removed. The skin wound was sutured. The surgery lasted 40 min. Blood loss was about 10 ml. There were no perioperative complications. Postoperative and gunshot wounds healed within 10 days supported by antibiotic therapy (Ceftriaxone 2.0 g per day). There was no cerebrospinal fluid leakage.

Size of the bullet: caliber 5.45 mm, length 23 mm. Postoperative computed tomography and magnetic resonance imaging showed the absence of the foreign body in the spinal canal and restoration of the subarachnoid space patency (**Supplementary Video 1**).

Within 3 months, the patient regained strength in his left foot. Paresis of the right foot flexors remained at the grade 4. Disorders of urination and defecation completely regressed, cutaneous sensation and sexual function were restored. Back pain was not a concern.

CLINICAL CASE NO. 2

A 39-year-old man referred to the neurosurgery clinic with back pain associated with recurrent retroperitoneal phlegmon. He reported that 13 years ago he had received a gunshot—a penetrating blind wound of the abdomen with a damage to the liver, gallbladder, duodenum, colon, L1-L2 vertebral bodies. The bullet had landed in the L1-L2 intervertebral disc. There had been no neurological disorders.

In order to eliminate consequences of the injury the patient received a staged surgical treatment on the abdominal organs; however, the surgeons had refrained from removing the bullet. The patient had fully recovered. During the last year, the patient suffered from recurrent retroperitoneal phlegmon accompanied by febrile fever and intense lumbar pain; his treatment involved four openings and drainages of purulent foci through retroperitoneal access. CT fistulography showed a thin fistulous tract between the retroperitoneal abscess cavity and the foreign body at the level of L1-L2 vertebrae (**Figure 2A**).

It was suggested that a probable cause of recurrent infectious process was a bullet, so it was decided to remove a foreign body from the spine through percutaneous transforaminal endoscopic access.

Surgery

After general anesthesia induction the patient was prone positioned; under fluoroscopy control in AP and lateral views,

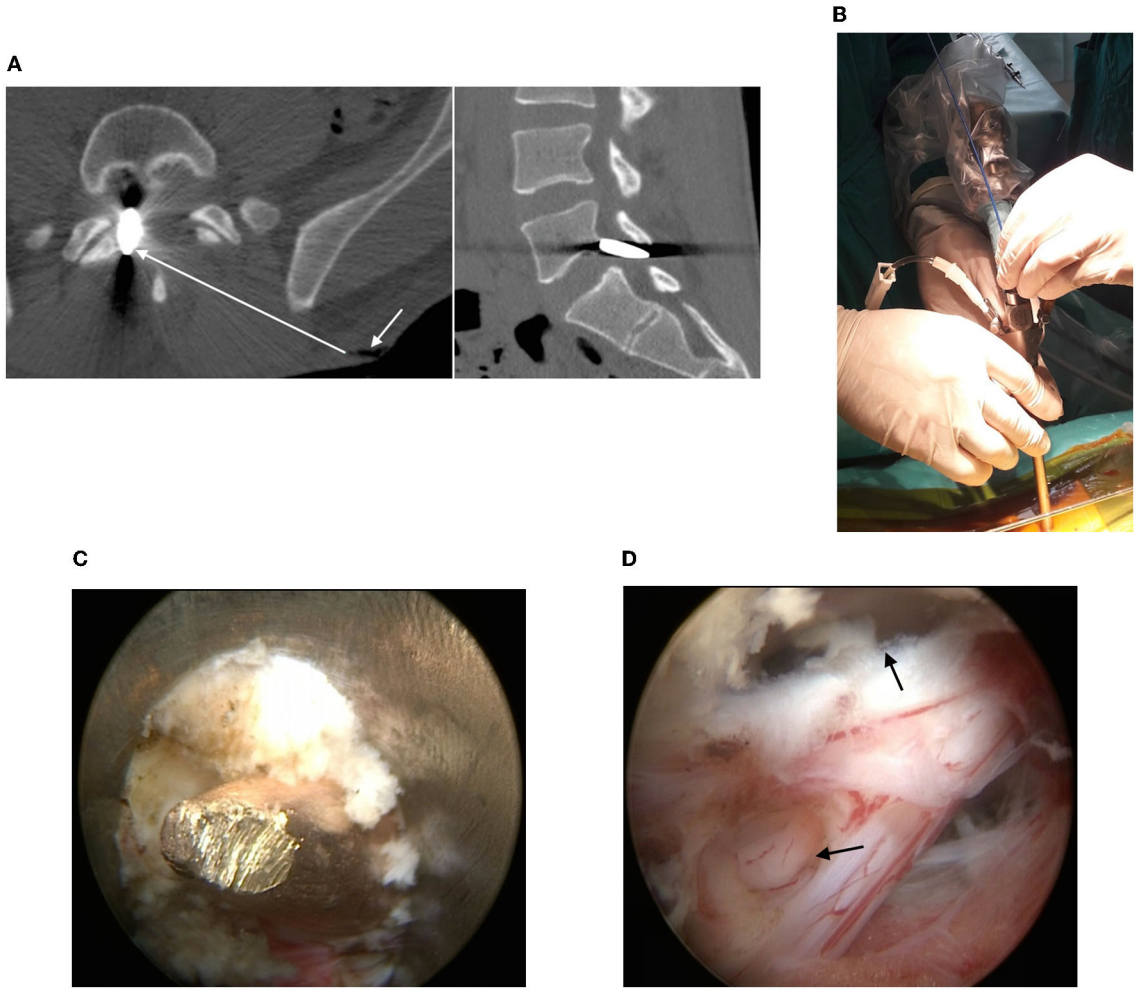

FIGURE 1 | (A) CT scans of the lumbar spine: metallic foreign body (bullet) in the right half of the spinal canal (the arrow shows the inlet of the gunshot wound, the line shows an approximate trajectory of the bullet through the soft tissues); **(B)** View of the working port and endoscope; **(C)** Bullet mobilization in a yellow ligament defect; **(D)** Defects in the dura mater around the nerve root cuff and dural sac (see arrows).

an 18G needle and a wire were inserted in the lower part of the left intervertebral foramen L1-L2. At the puncture site, a 1.0 cm long transverse incision of the skin and soft tissues was made. A cone-shaped guide and a working tube were inserted along the wire. The guide and wire are removed (**Figure 2B**). A SpineTip endoscope (Karl Storz, Germany) was inserted into the working tube. Further surgery was controlled by video endoscopy, which visualized bone markers of the intervertebral foramen and anterior epidural space. Fragments of the intervertebral disc back were removed. The bullet was detected. The bullet shell was destroyed, and difficult to separate from the surrounding tissues, which have a dirty gray color and numerous metal inclusions (**Figure 2C**). In order to form a channel for mobilization and extraction of the bullet, the lower edge of the L1 vertebra body was partially resected with a high-speed burr. The bullet was mobilized with hooks and scoops, fixed with forceps, and removed together with the working tube (**Figure 2D**). Under fluoroscopic control, the working tube and endoscope were reinserted transforaminally into the L1-L2 intervertebral disc, where there were many bullet shell fragments, removed with forceps and cutters (**Figure 2E**). Some fragments of the shell with surrounding soft tissues were taken for bacteria culture tests. Hemostasis was controlled by bipolar coagulation. After the last revision of the surgical wound, the working tube and the endoscope were removed. The skin wound was sutured with an interrupted suture. Surgery blood loss was <20 ml. During the surgery, the patient received antibiotic therapy with Vancomycin 1.0 g intravenously. The surgery lasted for 50 min (**Supplementary Video 2**).

The patient was mobilized the next day after the surgery. For 2 days he had an increased body temperature to 37.8°C, then the temperature got back to normal. The patient received antibacterial therapy (Cefazolin 2.0 g) for 7 days. The bacteria culture test of the sample taken during the surgery revealed *Escherichia coli*, sensitive to most antibiotics. On the 7th day after the surgery, the patient was discharged from the hospital. Upon

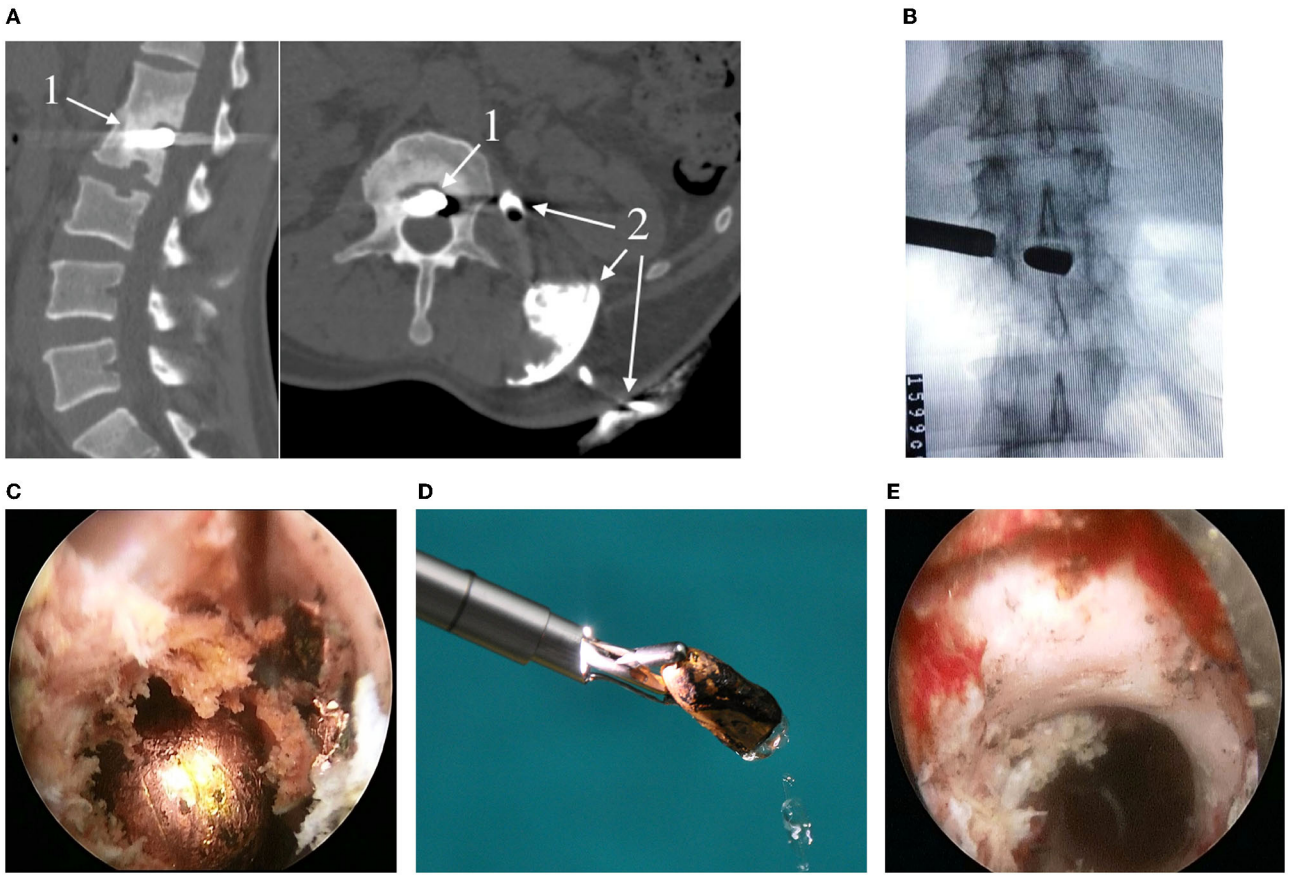

FIGURE 2 | (A) Preoperative sagittal CT (left) and CT fistulography (right) of the lumbar spine: 1—bullet; 2—contrast agent; **(B)** Radiography of the working port and bullet; **(C)** Endoscopic stage of the surgery and view of the bullet (described in the text); **(D)** Capturing and extracting the bullet with forceps (caliber 7.62 mm, length 15 mm); **(E)** Endoscopic view of the intervertebral foramen after extracting the bullet.

discharge, he had no complaints; the neurological status was at the preoperative level.

CLINICAL CASE NO. 3

A 19-year-old man was admitted to the neurosurgery clinic with a bullet wound in the back from an air gun. Upon admission he complained of thoracic spine pain. A physical examination of the thoracic spine showed an inlet with a size 0.3 × 0.5 mm. There were no signs of cerebrospinal fluid leakage and bleeding, no neurological disorders. X-ray of the chest in the Th8-Th9 vertebrae showed a foreign body—a bullet. CT scan of the thoracic spine also showed a metal-density foreign body in the spinal canal under the lamina of the Th8 vertebral arch (**Figure 3A**).

It was decided to make a full-endoscopic intervention to extract the foreign body from the spinal canal at the level of Th8-Th9 vertebrae.

Surgery

After general anesthesia induction the patient was prone positioned; under fluoroscopy control in AP and lateral views at the level of the Th8 vertebra arch, 2 cm outward and left to the midline, an 18G needle and a wire were sequentially inserted slightly above the bullet wound inlet. The needle was removed. Through a skin incision 1.0 cm long, a cone-shaped guide was inserted along the wire; a working tube was inserted along the cone-shaped guide, and an endoscope (Joimax, Germany) was inserted into the working tube (**Figure 3B**). With the help of a diamond burr, the arch of the Th8 vertebra was resected in a limited area. Within the yellow ligament there was a rounded defect, in its lumen a bullet was seen. After additional flavotomy, the bullet was removed from the spinal canal with the help of forceps (**Figure 3C**). Through the defect of the yellow ligament, the endoscope was introduced into the epidural space. The dura mater of the spinal cord showed no signs of impairment (**Figure 3D**). The dural sac had a distinct pulsation. Hemostasis was supported by bipolar coagulation. After a last revision of the surgical wound, the working tube and the endoscope was removed. The skin wound was sutured with an interrupted suture. The blood loss was <10 ml. The surgery lasted 40 min.

The patient stayed in the hospital for 3 days. At the time of discharge, the patient had no complaints. Neurological status was at the preoperative level.

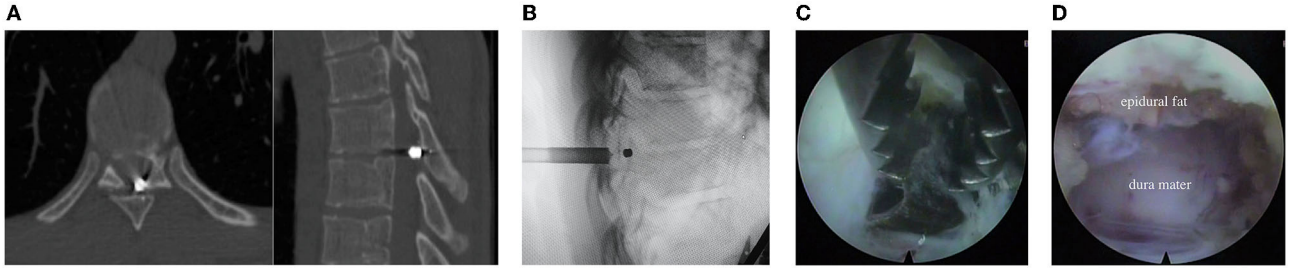

FIGURE 3 | (A) CT scans of the thoracic spine (explained in the text); **(B)** Radiography of the working port and bullet; **(C,D)** Endoscopic stage of the surgery (described in the text).

DISCUSSION

Gunshot wounds of the spine and spinal cord in peacetime and wartime make 10–21% of all spinal injuries (7–9). In 2014 in the United States, 16.8% (33,594 people) of deaths from injuries were associated with damaging effects of firearms (10). Males aged 15–34 years are more likely to be affected by this type of injury (various authors, 78–91%), 10–24.5% are lumbar spine injuries, of which penetrating injuries make about 14% (9, 11–14). Gunshot wounds of the spine are often accompanied with injuries to the neck, chest, abdominal cavity and retroperitoneal space. A key factor to make prognosis in the acute and early periods of combined injuries is emergency surgery on the damaged vessels and organs (13).

So far, there is no generally approved medical care algorithm for such patients. Such factors as indications amount, reason and time of surgical intervention remain relevant (9, 15–17). A standard procedure in diagnosing spine gunshot wounds is computed tomography, which allows assessing position of the bullet and degree of bone damage (15).

Surgical treatment of spine gunshot wounds is needed in the following cases: increased neurological deficit, neural structures compressed by a bone fragment, intervertebral disc or foreign body, cerebrospinal fluid leakage, gunshot penetrating blind injury to the spinal cord cone and cauda equina, spinal instability, infectious complications and pain syndromes in the late injury period (18, 19). The purpose of the surgery in penetrating blind wounds is to remove a foreign body, decompress neurovascular lesions of the spinal canal, and restore integrity of the dura mater and patency of the subarachnoid space (15).

Despite the obvious indications listed above, the effectiveness of surgical treatment of gunshot wounds to the spinal cord remains low. Treatment outcomes for those with gunshot wounds to the cervical and thoracic spine, in the absence of positive dynamics in neurological status, did not differ between conservative and surgical groups (16).

The necessity of removal of a wounding body in uncomplicated non-penetrating gunshot wounds of the spine, especially in the late period, is still open for discussion. Experts differ on the toxic effects of lead when a wounding body remains for a long time (10, 20); however, there is no doubt that a foreign body must be removed in cases of purulent-inflammatory complications (21).

Surgeons should carefully select an access to the spine for bullet removal, and be guided by the position of the bullet against parts of the spinal canal and neurovascular structures. The most common and universal method for accessing a bullet in the spinal canal is laminectomy (9). Lateral and anterior approaches are typical for the removal of foreign bodies from the intervertebral disc and vertebral bodies (21). Given that most gunshot wounds do not impair spinal stability, stabilizing aids are usually not required. Hence, such cases require minimally invasive surgical treatments.

There are some published reports on the microsurgical removal of a wounding body through a tube retractor through a posterior access along the optimal trajectory. This method proved to be very efficient in terms of regression of neurological dysfunctions and prevention of infectious complications in a spine gunshot wound (10, 22).

Nowadays, the least invasive surgical method in spinal surgery is percutaneous video endoscopy. Advantages of this method, like any minimally invasive technology, are well known and relate to clinical and economic aspects. Technical characteristics of spinal percutaneous endoscopic interventions ensure a targeted approach to a surgical target both through natural anatomical spaces of the vertebral segments (interlaminar space, intervertebral foramen), and through intervertebral discs and bone structures (23). Such interventions greatly reduce infectious complications afterwards (24). Although there are lots of papers devoted to full-endoscopic spinal surgery, its use in spine gunshot wounds has not yet been thoroughly discussed (2).

Of course, percutaneous video endoscopic aids are still inferior to open access in terms of comprehensive revision, sanitation and drainage of gunshot wounds, especially in case of multiple spinal injuries (shot, buckshot, etc.) (10). Disadvantages of full-endoscopic removal of a bullet from the spinal canal include the impossibility of complete sealing of defects in the dura mater. However, puncture endoscopic access, apparently, prevents appearance of cerebrospinal fluid cysts and fistulas. Clinical application of percutaneous unilateral biportal endoscopic technique (25, 26) and technical aids for full-endoscopic closure of defects in the dura mater of the spinal cord (27) promise a successful solution of such problems in future.

CONCLUSION

Full-endoscopic operations can be effective in bullet wounds to the spine. Their application allows:

1) to remove the bullet from the spinal canal or intervertebral disc;
2) to inspect the epidural and subdural spaces of the spine;
3) reduce the risk of infectious complications through minimal invasiveness, sanitation and continuous intraoperative irrigation of the gunshot wound with saline sodium chloride solution;
4) perform plasty of the dura mater defect.

These operations should be performed at the tertiary care level by surgeons with sufficient experience in percutaneous endoscopic spinal surgery.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

MK, GB, and SM contributed to the conception and design of the study, the analysis and interpretation of data, and the work draft. MK designed figures and video. VM and VB offered guidance in study design and revised the article critically for important intellectual content. All authors read and approved the final version of the manuscript.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsurg.2022.873365/full#supplementary-material

Supplementary Video 1 | Full-endoscopic surgery for gunshot wound of the lumbar spine: a report of case.

Supplementary Video 2 | Full-endoscopic transforaminal surgery for gunshot wound of the lumbar spine: a report of case.

REFERENCES

1. Shin JK, Youn MS, Seong YJ, Goh TS, Lee JS. Iatrogenic dural tear in endoscopic lumbar spinal surgery: full endoscopic dural suture repair (Youn's technique). *Eur Spine J.* (2018) 27:544–8. doi: 10.1007/s00586-018-5637-6
2. Telfeian AE, Veeravagu A, Oyelese AA, Gokaslan ZL. A brief history of endoscopic spine surgery. *Neurosurg Focus*. (2016) 40:E2. doi: 10.3171/2015.11.FOCUS15429
3. Wagner R, Telfeian AE, Iprenburg M, Krzok G, Gokaslan Z, Choi DB, et al. Transforaminal endoscopic solution to a kyphoplasty complication. *World Neurosurg.* (2016) 91:195–8. doi: 10.1016/j.wneu.2016.04.013
4. Ito M, Abumi K, Kotani Y, Kadoya K, Minami A. Clinical outcome of posterolateral endoscopic surgery for pyogenic spondylodiscitis: results of 15 patients with serious comorbid conditions. *Spine.* (2007) 32:200–6. doi: 10.1097/01.brs.0000251645.58076.96
5. Sentürk S, Ünsal ÜÜ. Percutaneous full-endoscopic removal of lumbar intradural extramedullary tumor via translaminar approach. *World Neurosurg.* (2019) 125:146–9. doi: 10.1016/j.wneu.2019.01.206
6. Konakondla S, Sofoluke N, Xia J, Grant R, Telfeian AE, Hofstetter CP, et al. Transforaminal endoscopic approach for large-sample tumor biopsy using beveled working channel for core technique: a technical note. *World Neurosurg.* (2020) 141:346–51. doi: 10.1016/j.wneu.2020.05.096
7. Schoenfeld AJ, Laughlin MD, McCriskin BJ, Bader JO, Waterman BR, Belmont PJ. Spinal injuries in United States military personnel deployed to Iraq and Afghanistan: an epidemiological investigation involving 7877 combat casualties from 2005 to 2009. *Spine.* (2013) 38:1770–8. doi: 10.1097/BRS.0b013e31829ef226
8. Beaty N, Slavin J, Diaz C, Zeleznick K, Ibrahimi D, Sansur CA. Cervical spine injury from gunshot wounds. *J Neurosurg Spine.* (2014) 21:442–9. doi: 10.3171/2014.5.SPINE13522
9. Jakoi A, Iorio J, Howell R, Zampini JM. Gunshot injuries of the spine. *Spine J.* (2015) 15:2077–85. doi: 10.1016/j.spinee.2015.06.007
10. Crutcher CL, Wilson JM, DiGiorgio AM, Fannin ES, Shields JA, Morrow KD, et al. Minimally invasive Management of Civilian Gunshot Wounds to the lumbar spine: a case series and technical report. *Operative Neurosurg.* (2020) 19:219–25. doi: 10.1093/ons/opaa030
11. Farmer JC, Vaccaro AR, Balderston RA, Albert TJ, Cotler J. The changing nature of admissions to a spinal cord injury center: violence on the rise. *J Spinal Disord.* (1998) 11:400–3. doi: 10.1097/00002517-199810000-00006
12. Bono C, Heary F. Gunshot wounds to the spine. *Spine J.* (2004) 4:230–40. doi: 10.1016/S1529-9430(03)00178-5
13. Mogila VV, Maksimov SA. Features spine gunshot wounds and spinal cord in the lumbar – sacral. *Tavricheskiy Mediko Biologicheskiy Vestnik.* (2013) 16:123–5.
14. Jaiswal M, Mittal RS. Concept of gunshot wound spine. *Asian Spine J.* (2013) 7:359–64. doi: 10.4184/asj.2013.7.4.359
15. Volkov PV, Grin AA. Surgical treatment strategy at patients with gun and stab wounds of vertebrae and spinal cord. *Russian J Neurosurg.* (2010) 2:72–9.
16. Sidhu GS, Ghag A, Prokuski V, Vaccaro AR, Radcliff KE. Civilian gunshot injuries of the spinal cord: a systematic review of the current literature spine. *Clin Orthop Relat Res.* (2013) 471:3945–55. doi: 10.1007/s11999-013-2901-2
17. Bumpass DB, Buchowski JM, Park A, Gray BL, Agarwal R, Baty J, et al. An update on civilian spinal gunshot wounds. *Spine.* (2015) 40:450–61. doi: 10.1097/BRS.0000000000000797
18. Hakan T, Çerçi A, Gürcan S, Akçay S. Firearm bullet settling into the lumbar spinal canal without causing neurological deficit: a report of two cases. *Surg Neurol Int.* (2016) 7:S251–4. doi: 10.4103/2152-7806.181978
19. Çiftçi U, Arinci AT, Delen E, Güçlühan D. Incomplete isolated C7 root injury caused by gunshot wound: a case report. *Korean J Neurotrauma.* (2017) 13:45–49. doi: 10.13004/kjnt.2017.13.1.45
20. Apte A, Bradford K, Dente C, Smith RN. Lead toxicity from retained bullet fragments: a systematic review and meta-analysis. *J Trauma Acute Care Surg.* (2019) 87:707–16. doi: 10.1097/TA.0000000000002287

21. Volkov PV, Sorokin KV. Long terms results of non-penetrative gunshot wound of lumbar spine with prevertebral abscess forming. *Russian J Neurosurg.* (2011) 4:69–73.
22. Shen FHT, Samartzis D. Operative management of a sacral gunshot injury via minimally invasive techniques and instrumentation. *Asian Spine J.* (2013) 7:44–9. doi: 10.4184/asj.2013.7.1.44
23. Hofstetter CP, Ahn Y, Choi G, Gibson JNA, Ruetten S, Zhou Y, et al. AOSpine consensus paper on nomenclature for Working-Channel endoscopic spinal procedures. *Global Spine J.* (2020) 10:111S−21S. doi: 10.1177/2192568219887364
24. Liu X, Yuan S, Tian Y, Wang L, Gong L, Zheng Y, et al. Comparison of percutaneous endoscopic transforaminal discectomy, microendoscopic discectomy, and microdiscectomy for symptomatic lumbar disc herniation: minimum 2-year follow-up results. *J Neurosurg Spine.* (2018) 28:317–25. doi: 10.3171/2017.6.SPINE172
25. Heo DH, Son SK, Eum JH, Park CK. Fully endoscopic lumbar interbody fusion using a percutaneous unilateral biportal endoscopic technique: technical note and preliminary clinical results. *Neurosurg Focus.* (2017) 43:E8. doi: 10.3171/2017.5.FOCUS17146
26. Kim JE, Yoo HS, Choi DJ, Park EJ, Jee SM. Comparison of minimal invasive versus biportal endoscopic transforaminal lumbar interbody fusion for single-level lumbar disease. *Clin Spine Surg.* (2020) 34:E64–71. doi: 10.1097/BSD.0000000000001024
27. Park HJ, Kim SK, Lee SC, Kim W, Han S, Kang SS. Dural tears in percutaneous biportal endoscopic spine surgery: anatomical location and management. *World Neurosurg.* (2020) 136:578–85. doi: 10.1016/j.wneu.2020.01.080

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ORIGINAL RESEARCH
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Transforaminal Endoscopic Discectomy Under General and Local Anesthesia: A Single-Center Study

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Percutaneous spinal endoscopy is used for the treatment of disorders of the lumbar spine, as it has several advantages over traditional surgical methods. The performance of percutaneous spinal endoscopy is not possible without applying anesthesia methods. Two types (local and general) of anesthesia are used for percutaneous spinal endoscopy. Both, local and general anesthesia approaches contribute to safety in surgical procedures. Although it is believed that the method of local anesthesia has more benefits over general anesthesia, such as lowering the risk of postoperative neurological complications in a patient, the literature on the topic is inconclusive. The study aims to perform a comparative analysis of the two anesthesia methods using a prospective case-control design. Patients were divided into two groups: those who received local anesthesia (LA) (20 patients), and those who underwent general anesthesia (GA) (20 patients). As a result of the study, 40% of the patients experienced moderate pain and 5% of the patients experienced excruciating pain intraoperatively in the LA group. Although Visual Analog Scale and Oswestry Disability Index scores improved more rapidly in LA group, at the 12-month check-up point there was no significant difference between cases and controls. Nevertheless, there were postoperative complications such as nerve root injury in 10% of the patients; nausea, vomiting, dizziness, drowsiness in 15% of the patients in the GA group, and an insignificant or no such complications in patients of the LA group. The present study demonstrates that LA contributes to more positive short-term outcomes for patients as it facilitates nerve root damage prevention, and has no postoperative side effects on patients' well being.

Keywords: transforaminal discectomy, local anesthesia, general anesthesia, lumbar spine, herniation

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INTRODUCTION

The methods of surgical treatment of herniated intervertebral disks of the lumbar spine are progressing and evolving each year to minimize postoperative complications and unintended consequences. Although the gold standard of the herniated disc surgical treatment is the open microdiscectomy, recently, numerous techniques have been developed to minimize the trauma of the surgical approach without reducing the radicalness of the surgical operation (1).

One of such techniques is percutaneous endoscopic spine endoscopy, which is a minimally invasive procedure that can be used to treat a variety of lumbar spine disorders. Percutaneous

endoscopic discectomy has demonstrated similar effectiveness to be open discectomy in treating lumbar disc herniation (2, 3). It has several advantages over the traditional open discectomy, such as less damage to the paravertebral muscles, less intraoperative blood loss, shorter postoperative hospitalization period, and early postoperative patient recovery. Percutaneous endoscopic lumbar discectomy is now becoming a routine operation in spine surgery. In most cases, percutaneous endoscopic discectomy is performed using the transforaminal approach, which can theoretically be used at all lumbar levels of the spine (4–6). However, it is sometimes difficult to perform transforaminal endoscopic discectomy for L5/S1 disc herniation due to the anatomical limitations in the lumbosacral region, such as the high iliac crest, large transverse spur of the L5 vertebrae, large facet joint, and narrow foraminal space (7).

Both general anesthesia (GA) and local anesthesia (LA) are commonly used in various endoscopic surgeries, including the transforaminal approach in the percutaneous endoscopic lumbar discectomy (8, 9). LA is recommended by most surgeons for the transforaminal approach in the percutaneous endoscopic lumbar discectomy, as it results in early functional recovery of patients, lowers nerve damage risks, and less intraoperative volume of blood loss. In addition, it allows surgeons to avoid pulmonary complications associated with the GA (10). Also, LA helps to reduce such frequent side effects of general anesthesia as sore throat, nausea, and vomiting, as well as headache and dizziness (11).

The LA approach also can lead to complications that may result in nerve root damage, rupture of the dura mater, hematoma, and intracranial hypertension (12). The patients' satisfaction and the surgeon's ability to perform prolonged surgery are two major benefits of GA.

There are still many debates about the feasibility, safety, and effectiveness of LA and GA in patients undergoing transforaminal endoscopic lumbar spine surgery. However, modern methods of GA, such as multimodal neopioid analgesia and accelerated approach, have not often been compared to LA. Thus, the present study aims to determine the type of anesthesia that provides the best clinical outcomes for patients undergoing the transforaminal approach in the percutaneous endoscopic lumbar discectomy.

MATERIALS AND METHODS

Study Population

The present research is a prospective case-control study. Forty patients diagnosed with lumbar disc herniation and treated using the transforaminal endoscopic discectomy between January 2020 and July 2020 at the Spinal Neurosurgery Department of the National Center for Neurosurgery, Nur-Sultan, Kazakhstan were enrolled in the study. Patients were divided into two groups. The first group underwent GA and the second group received LA.

Patients who were diagnosed with single-level lumbar disc herniation, confirmed through magnetic resonance imaging (MRI), with typical irradiating pain in the legs, and failure of conservative treatment methods at least 3 months before the hospitalization were included in the study.

Patients with interlaminar endoscopic discectomy, lumbar spine stenosis or other spinal pathology, a history of lumbar spondylodesis surgery, extreme lateral lumbar spinal hernia, and active local or systemic infection were excluded from the study.

Clinical Outcomes

Length of hospital stay (sum of days before and after the procedure), operation length, and intensity of intraoperative pain and neurological complications were recorded.

Study Instruments

Patients were asked to fill out the Visual Analog Scale (VAS) before the procedure, 3, 6, and 12 months after the procedure to measure the pain perception in the leg and back. The Oswestry Disability Index (ODI) was used to measure the severity of the functional disability that patients experienced due to herniated disc. Patients were asked to fill out the questionnaire before the procedure, 3 months after, 6 months after, and 12 months after the procedure.

Anesthesia and Surgical Procedure

Patients of the LA group were administered 10 ml of 0.5% lidocaine and 0.25% ropivacaine at a dose of 1.3 mg/kg to prevent associated pain. The group GA patients received 2–3 mg/kg propofol and 1 mg/kg fentanyl to facilitate endotracheal intubation. Muscle relaxation during intubation 1 mg/kg suxamethonium chloride, 0.05–0.02 mg/kg pipecuronium bromide.

All surgical operations were performed with the endoscopic system (Richard Wolf Riwospine, Germany). The level of surgical intervention was determined using intraoperative fluoroscopy. The surgery was performed in the abdomen position on the spinal framework. The injection point of the cannula was determined preoperatively based on the CT and MRI images. The location of the cannula varied among patients depending on the anatomical and physiological characteristics and was ∼8–12 cm from the midline. "The Walking Technique" was used to ensure

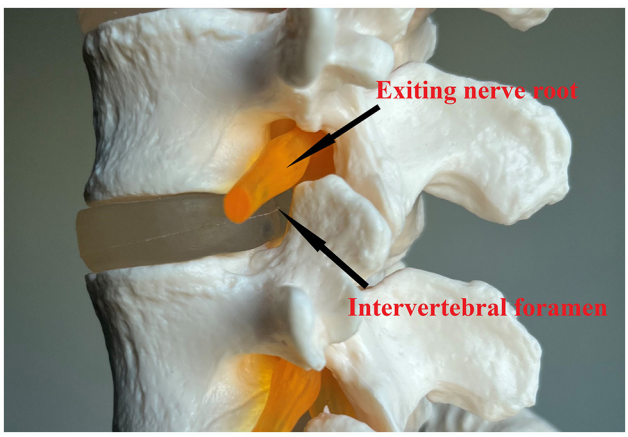

FIGURE 1 | Anatomical location of the exiting nerve root, intervertebral foramen and safety triangle.

safe access to the herniated glomerular nucleus through the safety triangle (**Figure 1**) Puncture needle was contacted with the caudal pedicle avoiding damage to the nerve root that exits from the cranial side of the intervertebral foramen. Then, using the walking technique, the needle was inserted into the intervertebral disc. A guide pin was inserted into the disc *via* the puncture needle, and the obturator and cannula were inserted sequentially through an 8-mm skin incision (**Figure 2**). After the cannula was inserted, the disc fragment at the base of the hernia was removed. Thereafter, using the inside-outside-down technique, the cannula was advanced toward the epidural space, the herniated mass was removed (**Figure 3**), and the pulsation of the dural tube was confirmed as an indicator of decompression (**Figure 4**). Patients were discharged when no signs of inflammation in the surgical wound were observed, and no pain syndromes were reported by patients.

The same surgical team, whose surgical experience exceeded 15 years in minimally invasive spine surgery, performed all the procedures.

Ethical Approval

Bioethics Committee of JSC National Center for Neurosurgery approved the study on 16 January 2020. The patient's written Informed Consent was obtained before the surgery.

Statistical Analysis

The patients' answers on VAS and ODI surveys, as well as the demographic and clinical characteristics, were entered into Excel. The patient scores were calculated at pre-operational, 3, 6, and 12 months points. Together with demographic and clinical characteristics their pain and disability scores were entered and cleaned in Excel [Microsoft Office (Microsoft Corp., Redmond, Washington, USA)] and analyzed using STATA software, version 16.0 (Stata- Corp, College Station, Texas, USA). Descriptive statistics of the data consisted of percentages, means, standard deviations, and frequencies. Association of variables was tested with Student's *t*-test and Fischer or chi-square tests where appropriate. A threshold of 0.05 *p*-value was used for the determination of statistical significance.

RESULTS

The mean age of the participants was 46.9 ± 11.2 years old. No statistically significant difference was observed between cases and controls. The proportion of male patients was slightly higher (57.5%) than female patients, but no significant difference was presented between general and local anesthesia groups.

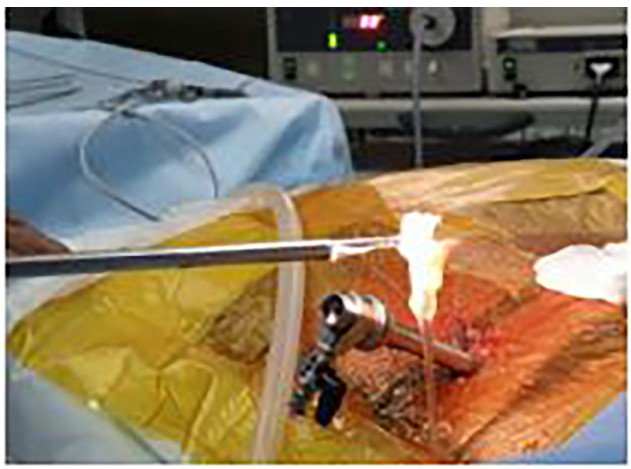

FIGURE 3 | Removal of the herniated nucleus pulposus.

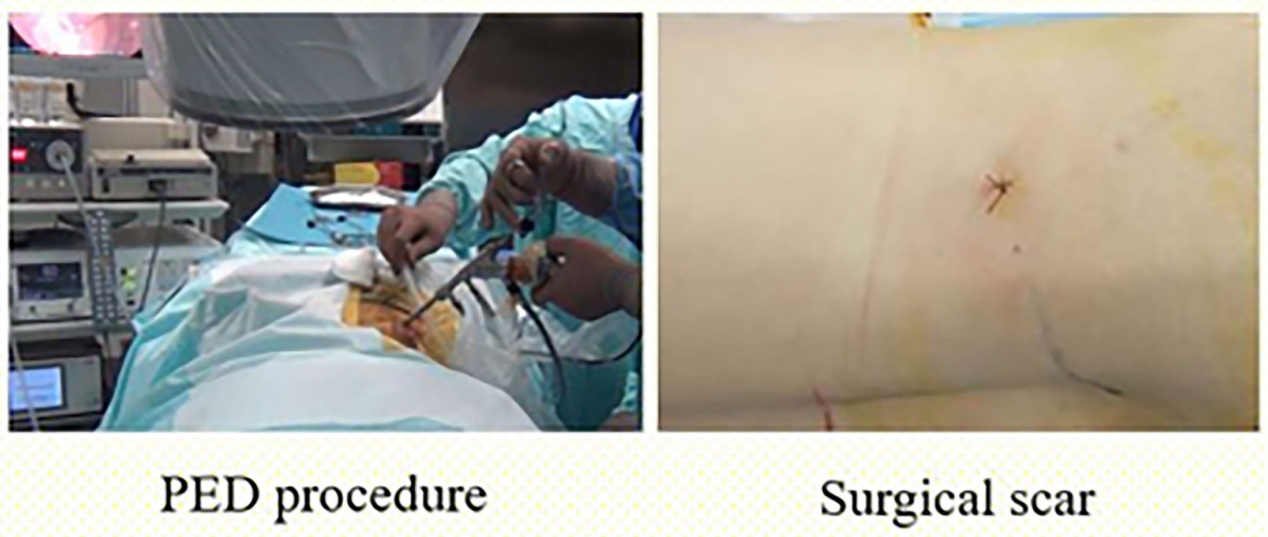

FIGURE 2 | Operative scene in percutaneous transforaminal endoscopic discectomy and the surgical incisional scar.

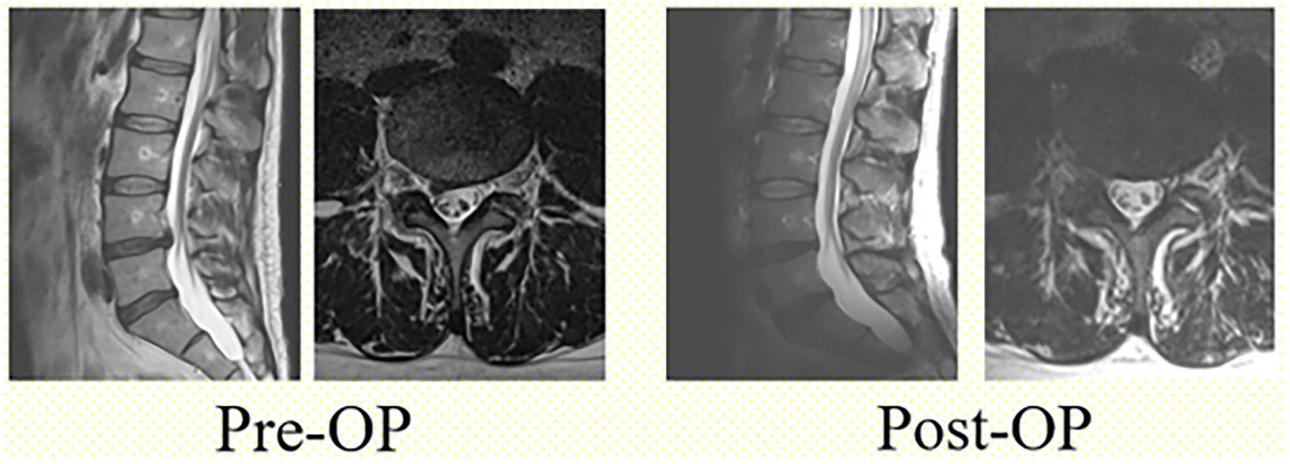

FIGURE 4 | T2-weighted sagittal and axial views before and after surgery.

TABLE 1 | The comparison of variables between two experimental groups.

Variable	General (mean ± SD)	Local (mean ± SD)	*p*-value	Overall (mean ± SD)
Age	47.6 ± 8.7	46.1 ± 13.5	0.68	46.9 ± 11.2
Sex				
Female	9 (52.94%)	8 (47.06%)	0.75	17 (42.5%)
Male	11 (47.83%)	12 (52.17%)		23 (57.5%)
Hospital stay (days)	5.1 ± 1.21	3.5 ± 1.1	<0.001	4.3 ± 1.4
Operation time (minutes)	75.6 ± 5.5	46.2 ± 9.3	<0.001	60.9 ± 16.7
VAS back before surgery	5.1 ± 0.9	5 ± 1.2	0.88	5.0 ± 1.1
VAS leg before surgery	8 ± 0.9	8 ± 1.1	1	8 ± 1.0
Change in VAS back 3 month (%)	57.5 ± 14.7	58.5 ± 16.9	0.85	58 ± 15.7
Change in VAS leg 3 month (%)	73.6 ± 9.1	75.1 ± 8.2	0.6	74.4 ± 8.6
Change in VAS back 6 month (%)	62.2 ± 17.4	77.9 ± 17.9	0.008	70 ± 19.2
Change in VAS leg 6 month (%)	74.8 ± 9.5	87.1 ± 7.6	<0.001	80.9 ± 10.6
Change in VAS back 12 month (%)	82.4 ± 14.2	80.8 ± 15.4	0.74	81.6 ± 14.7
Change in VAS leg 12 month (%)	85.8 ± 9.0	98.7 ± 4.1	<0.001	92.2 ± 9.5
ODI before surgery	50.0 ± 5.9	48 ± 8.2	0.39	49. ± 7.1
ODI 3 months	55.6 ± 6.1	61.8 ± 7.6	0.007	58.7 ± 7.5
ODI 6 months	59.4 ± 5.9	62.5 ± 7.3	0.14	61 ± 6.7
ODI 12 months	63.6 ± 4.3	63.8 ± 6.6	0.94	63.7 ± 5.5

The hospital stay length of the general anesthesia group was significantly longer (5.1 ± 1.2 days), when compared to the local anesthesia group (3.5 ± 1.1 days). Operation time was also significantly shorter among the local anesthesia group (46.2 ± 9.3 min) when compared to the general anesthesia group (75.6 ± 5.5 min).

The VAS score in the back and leg was similar in both groups before the surgery. Three months after the procedure the pain decreased ∼60% in the back and almost 75% in the leg with no significant difference between cases and controls. At 6 months point, those who were in the LA group reported an almost 78% decrease in back pain, while those in the GA group reported a 62% change. Change in leg pain perception followed a similar pattern with 87 vs. 75% decrease in local and general anesthesia groups respectively. There was no significant difference at 12 months point in the decrease of back pain between the groups (81% local, 82% general). However, the decrease in leg pain at 12 months was significantly higher in the local anesthesia group (99%), when compared to the general anesthesia group (86%) (**Table 1**).

No significant difference was observed in pre-operational ODI between LA (48 ± 8.3) and GA (50 ± 5.9) groups. The decrease in ODI scores was significantly higher in the LA group (61.8 ± 7.6) when compared to the GA group (55.6 ± 6.1) 3 months after the surgery. Six and 12 months after the procedure the decrease in ODI was similar in both groups lowering by almost 64% (**Figure 5**).

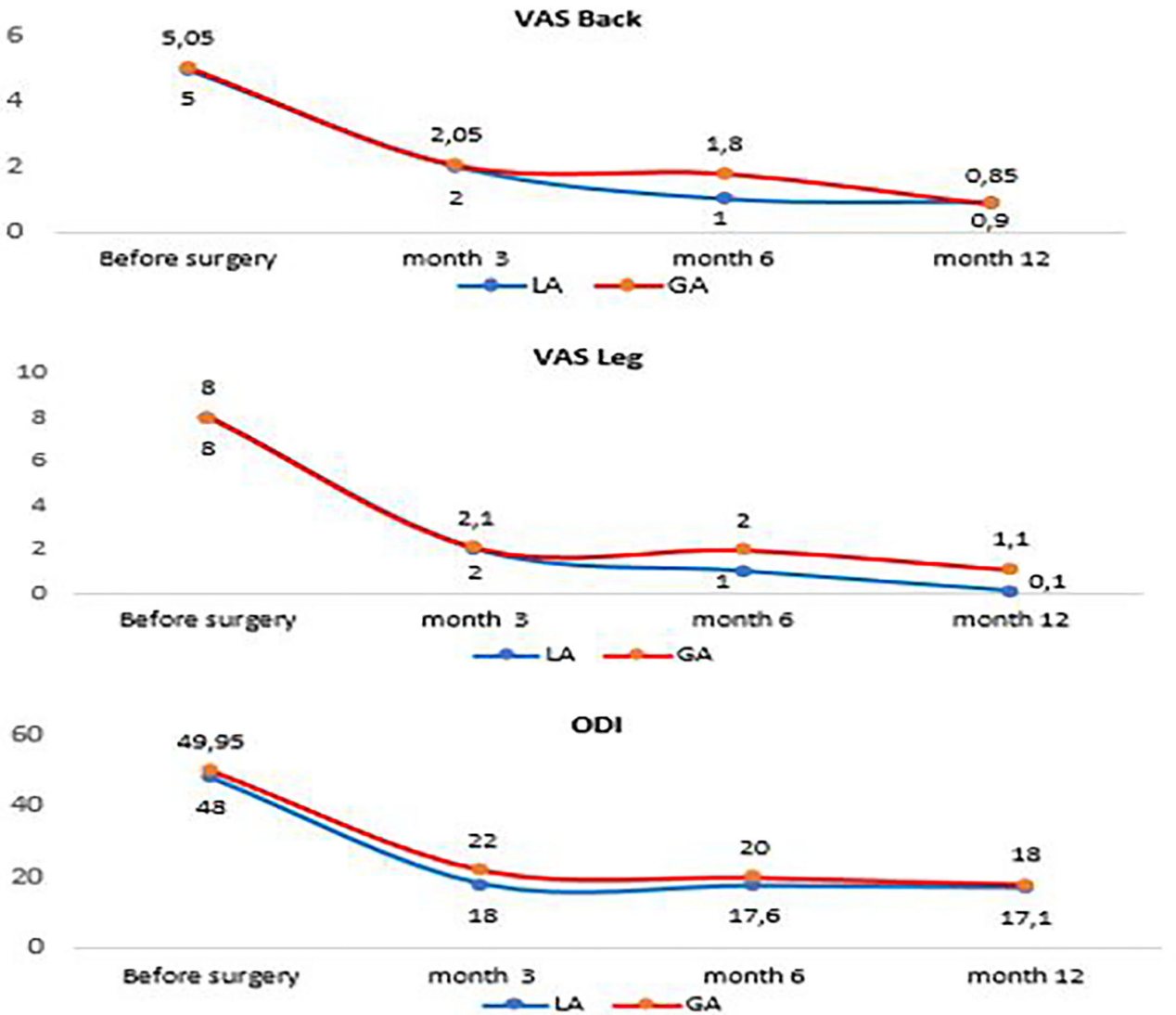

FIGURE 5 | Comparison of ODI, VAS between the local group and the general group.

In two patients in the GA group in a period of 5 months after the restorative treatment, patients' muscle strength had improved from grade 1 to grade 4. Patients in the LA group have reported a feeling of pain during surgery (40%) and excruciating pain (5%) during surgery. None of the patients in the GA group had such experiences. One patient (5%) in the LA group has experienced a nausea side effect. In the GA group 3 patients (15%) had experienced nausea, vomiting, dizziness, drowsiness, and 2 patients (10%) had sustained nerve root injury (**Table 2**).

DISCUSSION

Several recent studies have shown LA as an effective, reliable, and successful alternative to GA in lumbar surgery (13, 14). The main drawback of GA is the sensory blockade that could lead to damage to the cauda equina nerve and nerve roots in patients, which is difficult to detect during surgery. For these reasons, most surgeons prefer LA to GA. However, LA has such disadvantages as surgical anxiety (15) and stress reactions caused by anesthesia, immunosuppression, and inflammatory processes (16). Wang and co-authors have found that continuous epidural anesthesia has more advantages than LA in improving the immune function of patients undergoing the percutaneous endoscopic lumbar discectomy for lumbar disc herniation. They also suggested that pain-free surgery would reduce adverse psychological effects, such as postoperative anxiety (17) and a recent study showed that patients prefer GA (18).

However, despite the disadvantages of LA mentioned above, this method still has more advantages over GA. For example,

TABLE 2 | Comparison of adverse reactions, patient feeling between the local group and the general group.

Adverse reactions and patient satisfaction	Local anesthesia 100% ($n = 20$)	General anesthesia 100% ($n = 20$)
Nausea	5% (1)	15% (3)
Vomiting	0% (0)	15% (3)
Dizziness	0% (0)	15% (3)
Drowsiness	0% (0)	15% (3)
Nerve root injury	0% (0)	10% (2)
Pain during surgery		
Moderate pain	40% (8)	0
Excruciating pain	5% (1)	0

a neurosurgeon can control the patient's intraoperative pain during percutaneous endoscopic spine surgery. Keeping a patient awake plays a crucial role in spinal endoscopy to avoid nerve damage and allows the endpoint of surgery to be determined. In addition, LA does not require preoperative patient fasting and allows a physician to avoid some of the routine procedures required for GA, such as for example, tracheal intubation. This, in turn, contributes to a patient's rehabilitation immediately after the surgical procedure. In addition, the surgical procedure does not require drugs and devices associated with anesthesia and GA. For this reason, LA is less expensive than GA, which is an important factor that many surgeons should consider for their patients.

The present study aimed to examine the advantages and disadvantages of different anesthesia methods in transformational endoscopic discectomy, a less invasive surgical procedure that has shown to have minimal multifidus muscle atrophy (19, 20).

No postoperative infection was observed in both LA and GA groups. Despite the lack of complications observed in our LA group, a significantly larger proportion of patients have experienced discomfort in form of pain during the procedure. Currently, many surgeons are paying increasing attention to patient intraoperative psychology. Comfortable surgical experience is becoming increasingly important, as a successful surgical practice is associated with excellent postoperative clinical outcomes (21, 22).

Despite the sub-optimal patient experience during the surgery, the LA group had a shorter length of hospital stay and shorter surgery duration when compared to the GA group. This could be due to the preparation time for GA and recovery time after the tracheal intubation of a patient. Moreover, the LA group had more rapid improvement in VAS and ODI scores. Six months after surgery patients in the LA group had a significantly sharper decline in pain than in the GA group. However, the GA patients have caught up with LA patients by the 12 months mark. ODI score had a similar pattern with better recovery at 3- and 6-months points, but no difference in results between GA and LA groups at 12 months post-surgery. Only leg pain levels had remained significantly lower in the LA group 12 months after the procedure.

The GA group alone had postoperative complications such as nerve root damage in two patients, as well as nausea, vomiting, dizziness, and somnolence in three cases. Although the nerve root injury did not result directly from GA, the lack of communication with the patient during the surgery is one of the main factors that resulted in root injury. The frequency of dizziness, vomiting, and other symptoms has a direct relationship with anesthesia methods. Most drugs and anesthetics have a potential emetic effect, which had a higher association with general anesthesia in our study.

Considering the clinical outcomes of the patients in our study both GA and LA are effective methods for percutaneous transforaminal endoscopic surgery. Both groups have similarly recovered at 12 months follow-up point. However, the recovery in the LA group as well as the frequency of complications was significantly better than in the GA group. Physicians should take into account the somatic status of the patients, clinical outcomes, as well as their psychological comfort. Despite the discomfort that may occur during the surgery, the LA approach is a promising alternative to GA in percutaneous transforaminal endoscopic surgery.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by JSC National Center for Neurosurgery, Nur-Sultan, Kazakhstan. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

TK: conceptualization. YK: data collection. TK, VA, YU, YK, ZT, and AP: surgical procedures. MO and NA: postoperative observation of patients. YK and ZT: writing draft. DB, YM, and SA: review and editing of manuscript. All authors contributed to the article and approved the submitted version.

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REFERENCES

1. Thami B, Vasilios I, Andreas FM, Ahmed B. Current concepts for lumbar disc herniation. *Int Orthopaedics.* (2019) 43:841–51. doi: 10.1007/s00264-018-4247-6
2. Alvi MA, Kerezoudis P, Wahood W, Goyal A, Bydon M. Operative approaches for lumbar disc herniation: a systematic review and multiple treatment meta-analysis of conventional and minimally invasive surgeries. *World Neurosurg.* (2018) 114:391–40. doi: 10.1016/j.wneu.2018.02.156
3. Ruan W, Feng F, Liu Z, Xie J, Cai L, Ping A. Comparison of percutaneous endoscopic lumbar discectomy versus open lumbar microdiscectomy for lumbar disc herniation: a meta-analysis. *Int J Surg.* (2016) 31:86–92. doi: 10.1016/j.ijsu.2016.05.061
4. Gadjradj PS, van Tulder MW, Dirven CM, Peul WC, Harhangi BS. Clinical outcomes after percutaneous transforaminal endoscopic discectomy for lumbar disc herniation: a prospective case series. *Neurosurg Focus.* (2016) 40:E3. doi: 10.3171/2015.10.FOCUS15484
5. Li X, Han Y, Di Z, Cui J, Pan J, Yang M, et al. Percutaneous endoscopic lumbar discectomy for lumbar disc herniation. *J Clinic Neurosci.* (2016) 33:19–27. doi: 10.1016/j.jocn.2016.01.043
6. Kamper SJ, Ostelo RW, Rubinstein SM, Nellensteijn JM, Peul WC, Arts MP, et al. Minimally invasive surgery for lumbar disc herniation: a systematic review and meta-analysis. *Euro Spine J.* (2014) 23:1021–43. doi: 10.1007/s00586-013-3161-2
7. Wang X, Zeng J, Nie H, Chen G, Li Z, Jiang H, et al. Percutaneous endoscopic interlaminar discectomy for pediatric lumbar disc herniation. *Childs Nerv Syst.* (2014) 30:897–902. doi: 10.1007/s00381-013-2320-4
8. Chen HT, Tsai CH, Chao SC, Kao TH, Chen YJ, Hsu HC, et al. Endoscopic discectomy of L5-S1 disc herniation *via* an interlaminar approach: prospective controlled study under local and general anesthesia. *Surg Neurol Int.* (2011) 2:93. doi: 10.4103/2152-7806.82570
9. Sairyo K, Egawa H, Matsuura T, Takahashi M, Higashino K, Sakai T, et al. State of the art: transforaminal approach for percutaneous endoscopic lumbar discectomy under local anesthesia. *J Med Invest.* (2014) 61:217–25. doi: 10.2152/jmi.61.217
10. Yeung A, Gore S. Endoscopic foraminal decompression for failed back surgery syndrome under local anesthesia. *Int J Spine Surg.* (2014) 14:1022. doi: 10.14444/1022
11. Edgcombe H, Carter K, Yarrow S. Anaesthesia in the prone position. *Br J Anaesth.* (2008) 100:165–83. doi: 10.1093/bja/aem380
12. Sairyo K, Matsuura T, Higashino K, Sakai T, Takata Y, Goda Y, et al. Surgery related complications in percutaneous endoscopic lumbar discectomy under local anesthesia. *J Med Invest.* (2014) 61:264–9. doi: 10.2152/jmi.61.264
13. Fernandez-Ordonez M, Tenias JM, Picazo-Yeste J. Spinal anesthesia versus general anesthesia in the surgical treatment of inguinal hernia. Cost-effectiveness analysis). *Rev Esp Anestesiol Reanim.* (2014) 61:254–61. doi: 10.1016/j.redar.2013.11.016
14. Nicassio N, Bobicchio P, Umari M, Tacconi L. Lumbar microdiscectomy under epidural anaesthesia with the patient in the sitting position: a prospective study. *J Clin Neurosci.* (2010) 17:1537–40. doi: 10.1016/j.jocn.2010.04.031
15. Gadjradj PS, Arjun Sharma JR, Harhangi BS. Quality of conscious sedation using dexmedetomidine during full-endoscopic transforaminal discectomy for sciatica: a prospective case series. *Acta Neurochirurgica.* (2022). doi: 10.1007/s00701-021-05100-x
16. Pearson AM, Lurie JD. Surgical versus nonoperative treatment: how do we choose the right approach to lumbar disc herniation? *Pain Manag.* (2014) 4:247–9. doi: 10.2217/pmt.14.28
17. Wang SJ, Chen BH, Wang P, Liu CS, Yu JM, Ma XX. The effect of percutaneous endoscopic lumbar discectomy under different anesthesia on pain and immunity of patients with prolapse of lumbar intervertebral disc. *Eur Rev Med Pharmacol Sci.* (2017) 21:2793–9. Available online at: https://www.europeanreview.org/wp/wp-content/uploads/2793-2799-Effect-of-anesthesia-on-pain-and-immunity-in-LDH.pdf
18. Gadjradj PS, Smeele NV, de Jong M, Depauw PR, van Tulder MW, de Bekker-Grob EW, et al. Patient preferences for treatment of lumbar disc herniation: a discrete choice experiment. *J Neurosurg Spine.* (2021) 26:1–9. doi: 10.3171/2021.8.SPINE21995
19. Byvaltsev VA, Kalinin AA, Giers MB, Shepelev VV, Pestryakov YY, Biryuchkov YM. Comparison of MRI visualization following minimally invasive and open TLIF: a retrospective single-center study. *Diagnostics (Basel).* (2021) 11:906. doi: 10.3390/diagnostics11050906
20. Akshulakov SK, Kerimbayev TT, Sekenova GT, Makimova GS. Analysis of the results of endoscopic surgical treatment for hernias of the lumbosacral disks. *Zh Vopr Neirokhir Im N N Burdenko.* (2005) 4:18–21. Available online at: https://pubmed.ncbi.nlm.nih.gov/16404960/
21. Mancuso CA, Duculan R, Stal M, Girardi FP. Patients' expectations of lumbar spine surgery. *Eur Spine J.* (2015) 24:2362–9. doi: 10.1007/s00586-014-3597-z
22. Mancuso CA, Duculan R, Cammisa FP, Sama AA, Hughes AP, Lebl DR, et al. Fulfillment of patients' expectations of lumbar and cervical spine surgery. *Spine J.* (2016) 16:1167–74. doi: 10.1016/j.spinee.2016.04.011

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CASE REPORT
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Case Report: Posterolateral Epidural Supra-C2-Root Approach (PESCA) for Biopsy of a Retro-Odontoid Lesions in Same Sitting After Occipitocervical Fixation and Decompression in a Case of Crowned Dens Syndrome With Brainstem Compression and Displacement

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Background: 'Crowned dens syndrome' (CDS) is a special form of calcium pyrophosphate dihydrate deposition disease which is characterized radiologically by a halo-like or crown-like distribution in the periodontoid region and clinically by cervical pain. Herein, we will describe our experience of posterolateral epidural supra-C2-root approach (PESCA) for biopsy of retro-odontoid lesions in one surgical session after occipitocervical fixation and decompression in a patient with CDS and massive brainstem compression.

Case Presentation: A 70-year-old woman presented to our department with a 4-week history of progressive walking impairment, neck pain, neck rigidity, fever, dizziness, slight palsy of the left hand, and multiple fall episodes. Magnetic resonance imaging (MRI) of the craniovertebral junction (CVJ) and cervical spine revealed a lesion of the odontoid process and the retro-odontoid region with mainly solid components, as well as small cystic components, and brainstem compression and displacement. In first step, fusion surgery of the CVJ C0–C4 was performed with occiptocervical decompression. After fusion and decompression the lower lateral part of the C1 arc and the lateral superior part of the left side of the C2 arc were removed. The entry point was located directly above the superior part of the C2 root. A biopsy of the lateral portions of the lesions was obtained by bioptic forceps under microscope guidance. Pathologic examination of the mass revealed deposition of birefringent crystals compatible with calcium pyrophosphate. In addition to the clinical symptoms (especially neck pain), the diagnosis of CDS was made.

Non-steroidal inflammatory drugs (NSAIDs) and colchicine (and later magnesium) were started. At follow-up examination 6 months after surgery, an MRI scan of the cervical spine revealed regression of the pannus and the cyst with replacement of the brainstem, clinical improvement of walking, and increased strength of the left hand.

Conclusions: This study demonstrates that PESCA can be used to obtain tissue for pathological analysis in one surgical sitting after fusion and decompression and that fusion, decompression, and PESCA (in the same session) together with subsequent conservative management could be a good alternative for the treatment of CDS.

Keywords: crowned dens syndrome, PESCA, odontoid process, Saethre-Chotzen-Syndrome, pannus

INTRODUCTION

Retro-odontoid pseudotumors are defined (1) as soft tissue proliferation at the atlantoaxial junction surrounding the region of the transverse ligament, and they might be associated with rheumatoid arthritis, microinstability, subluxation, as well as crystal deposition diseases (1).

Joyce et al. (2) pointed out that the term pannus is used in several medical contexts and that in rheumatology, pannus is defined as an "aggressive structure in the inflamed rheumatoid joint that invades cartilage and bone, thereby causing irreversible joint damage." Pannus involves the atlanto-axial joint in rheumatoid arthritis and can cause instability and spinal cord injury due to compression of the cervicomedullary junction (2, 3), but it has also been used to describe retro-odontoid soft tissue masses in patients with juvenile idiopathic arthritis, spondyloarthritis, and calcium pyrophosphate dihydrate deposition (CPPD) disease (2).

Retro-odontoid pannus may develop in the spinal canal (4), may cause compression of the brainstem, may result in quadriplegia, or may even lead to sudden death in rare cases (5).

Crystal deposition diseases comprise a group of metabolic diseases, such as CPPD or hydroxyapatite crystal deposition (HAD), in which crystals are deposited in and around the joints and create inflammatory and destructive lesions (6).

While CPPD is the third most common inflammatory arthritis, characterized by acute (formerly known as pseudogout (7)) or chronic inflammation caused by deposits of CPP crystals in the articular cartilage and periarticular soft tissues, mostly in the knees and wrists (7), HAD is a systemic condition of unknown etiology (8).

In 1985, Bouvet et al. (9) first named a special form of CPPD (or HAD (10, 11)), which is characterized radiologically by a halo-like or crown-like distribution in the periodontoid region and clinically by cervical pain as 'crowned dens syndrome (CDS)' (6, 12–15). In most cases, CDS is managed conservatively, but in some rare cases with brainstem compression, myelopathy, and so on, surgery can be considered.

In a previous publication, we advocated for the posterolateral epidural supra-C2-root approach (PESCA) for biopsy of lesions of the odontoid process (OP) in one surgical session after occipitocervical fixation and decompression, which might be a good alternative to classical approaches (16).

Herein, we will describe our experience of PESCA for biopsy of retro-odontoid lesions in one surgical session after occipitocervical fixation and decompression in a patient with CDS and massive brainstem compression.

To best of our knowledge this is the first case of CDS which had been managed by this concept.

CASE PRESENTATION

A 70-year-old woman presented to our department with a 4-week history of progressive walking impairment, neck pain, neck rigidity, fever, dizziness, slight palsy of the left hand, and multiple fall episodes.

Magnetic resonance imaging (MRI) of the craniovertebral junction (CVJ) and cervical spine revealed a lesion of the OP and the retro-odontoid region (**Figures 1A,B**) with mainly solid components, as well as small cystic components (**Figure 1C**), and brainstem compression and displacement (differential diagnoses include metastasis, rheumatoid arthritis, and spondylodiscitis) (**Figures 1C,D**). Computed tomography (CT) revealed spinal stenosis and odontoid erosion with signs of instability (**Figures 1F–H**).

The patient had a history of Saethre–Chotzen syndrome (SCS) (also known as acrocephalosyndactyly type III) and diabetes mellitus with diabetic nephropathy. MRI also revealed a fusion of the cervical vertebral bodies C3 to C6 due to Saethre-Chotzen syndrome (**Figure 1A**).

Owing to brainstem compression and displacement caused by pannus grade 4, cervical instability, and progressive walking impairment, we decided to perform surgery. Our goal was to stabilize the CVJ, decompress the foramen magnum and spinal canal at the C1 level, and perform biopsy of the periodontoid lesion for pathological analysis in a single surgical session.

Intervention

Preoperative planning included a thin slice CT image of the cervical spine and CVJ for spinal neuronavigation, CT angiography (CTA) for analysis of the V3 segment of the vertebral artery, which revealed a "normal" anatomy, and a three-dimensional model print (1:1 scale model using the fused filament fabrication).

Cefuroxime was administered for perioperative surgical prophylaxis. The patient was placed in a prone position

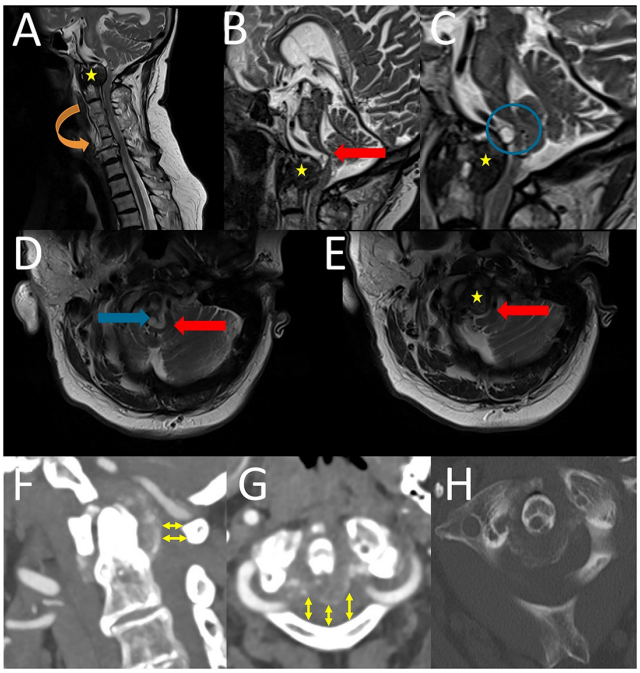

FIGURE 1 | Preoperative sagittal **(A–C)** and axial **(D,E)** T2-weigthed magnetic resonance images revealed a lesion of the OP and the retro-odontoid region (yellow stars) with brainstem compression and displacement (red block arrows) and also cystic component (blue block arrows and blue circle). Furthermore, the cervical vertebral bodies C3 to C6 were fused due to Saethre-Chotzen syndrome (orange block arrow). Preoperative CT and CTA of cervical spine **(F–H)**: A sagittal **(F)** and an axial **(G)** CTA (soft tissue window) revealed a "normal" anatomy of the vertebral artery and furthermore a spinal stenosis in the level of C 1 (yelow arrows). An axial CT (bone window) showed a "horseshoe" or "crown-like" calcification, which is located posterior to the OP **(H)**.

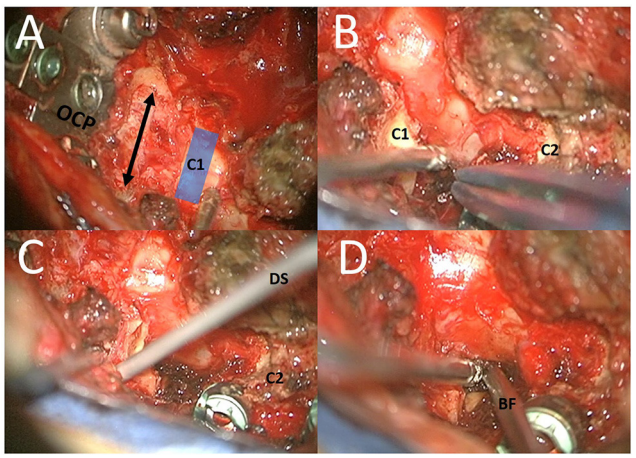

FIGURE 2 | Different steps of surgery: **(A)** In first step, fusion surgery of the CVJ C0–C4 was performed with an OC plate (OCP) with occiptocervical decompression (by enlargement of the foramen magnum and laminectomy of the medial C1 arc); **(B,C)** After fusion and decompression the lower lateral part of the C1 arc (subperiostal, with remnant upper C1 arc) and the lateral superior part of the left side of the C2 arc. Doppler sonography (DS) was used to analyze the anatomy of vertebral artery. **(D)** The entry point was located directly above the superior part of the C2 root. The trajectory was located medial to the pedicle of C2, medial to the C1–C2 facet joint, and medial to the tubercle for the transverse ligament of the atlas. A biopsy of the lateral portions of the lesions was obtained by bioptic forceps (BF) under microscope guidance.

under general anesthesia, and radiography was performed after positioning to verify anatomical alignment. Intraoperative monitoring (IOM) included motor-evoked potentials and sensory-evoked potentials of the upper and lower extremities.

A midline incision was made and the inion, posterior wall of the posterior cranial fossa, C1 arc, and C2, C3, and C4 laminae were exposed.

Fusion surgery of the CVJ C0–C4 was performed with an OC plate (MOUNTAINEER, DePuy Synthes, Raynham, MA, USA) under spinal neuronavigation (Brainlab).

After fusion, the foramen magnum was enlarged under microscope (ZEISS KINEVO, Carl Zeiss, Germany) examination. Laminectomy of the medial C1 arc and the lower lateral part of the C1 arc (subperiostal, with remnant upper C1 arc), removal of the left superior part of the left side of the C2 arc, and flavectomy were performed (**Figure 2**). Doppler sonography was used to analyze the anatomy of vertebral artery (**Figure 2**).

Different landmarks such as the C2 root and remains of the C1 arc, C2 arc, and dural sac were identified. Then, PESCA, which we described in a previous publication, was performed (16).

The window between the remains of the C2 arc and the C2 root was used in our approach. The entry point was located directly above the superior part of the C2 root. The trajectory was located medial to the pedicle of C2, medial to the C1–C2 facet joint, and medial to the tubercle for the transverse ligament of the atlas.

A bioptic instrument was inserted under microscope guidance (**Figure 2**). Owing to dorsal decompression, the danger of compression was limited as much as possible. IOM remained stable during surgery. A biopsy of the lateral portions of the lesions was obtained.

Postoperative Course

A postoperative CT scan showed proper positioning of the screws and sufficient decompression of the spinal cord at the level of the CVJ (**Figures 3A–C**). The patient recovered from surgery without any new deficits.

Pathologic examination of the mass revealed fibrous connective tissue with deposition of birefringent crystals compatible with calcium pyrophosphate (CPP) due to CPPD disease (**Figures 3D,E**). In addition to the clinical symptoms (especially neck pain), the diagnosis of CDS was made. Non-steroidal inflammatory drugs (NSAIDs) and colchicine were started.

Follow-Up

At follow-up examination 3 months after surgery, the patient did not manifest any neurological symptoms, and the CT scan of the CVJ did not reveal large regression of the pannus. Therefore, NSAIDs (diclofenac), steroids (prednisolone), and magnesium were administered.

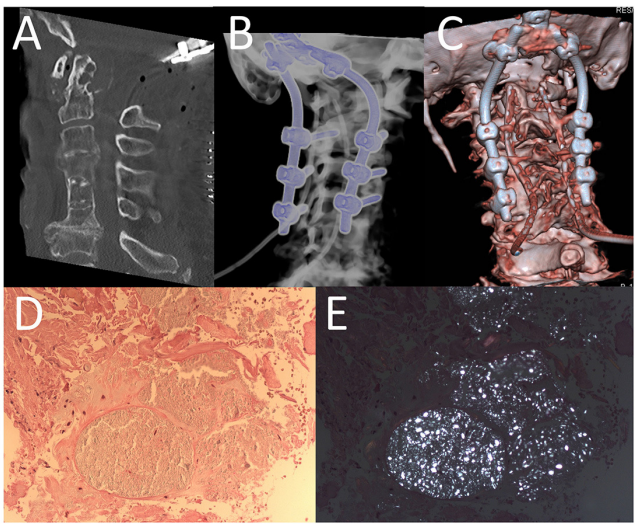

FIGURE 3 | Post-operative CT-scan of cervical spine **(A)** and different three-dimensional reconstruction **(B,C)** revealed a sufficient decompression and furthermore regular placement of screws. Histopathologic findings of bioptic probe showing fibrous connective tissue (HE x 200) **(D)** with multifocal deposits of birefringent crystals (under polarized light x 200) **(E)**.

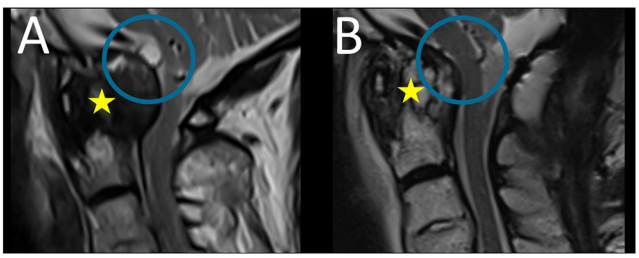

FIGURE 4 | Preoperative **(A)** and follow-up **(B)** sagittal T2-weigthed magnetic resonance images: follow-up MRI scan revealed regression of the pannus (yellow star) and the cyst with replacement of the brainstem (blue circle).

At follow-up examination 6 months after surgery, an MRI scan of the cervical spine revealed regression of the pannus and the cyst with replacement of the brainstem (**Figure 4**), clinical improvement of walking, and increased strength of the left hand. Since then, the patient did not experience neck pain and dizziness.

DISCUSSION

Crowned Dens Syndrome

Oka et al. (17) summarized in their review 72 published cases of CDS (including their own three cases) and found that the mean patient age was 71.4 (26–93) years, 47.2% of the patients were male, 52.8% were female, and 54.1% had peripheral arthritis. Furthermore, they concluded that the classical triad of CDS is neck pain (100%), neck rigidity (98%), and fever (80.4%). Besides these symptoms, 19.1% of the patients had shoulder pain and 8.3% experienced occipital or temporal pain (17). Myelopathy was detected in 5.5% of the cases (17).

The precise diagnosis of CDS might be challenging (17–19), as the symptoms are similar to those of other diseases, such as spondylodiscitis, meningitis, cervicobrachial pain, polymyalgia rheumatism, occipitotemporal headache, giant cell arteritis, calcific tendinitis of the longus colli muscle, and retropharyngeal abscess.

Radiological Diagnosis

Different authors concluded that CT of the CVJ is the gold standard for the diagnosis of CDS (13, 17). The goal is to detect the horseshoe or crown-like calcification (13), which is located posterior to the OP in approximately 90% of cases (19), but also might be located in different structures around the OP such as the transverse ligament, alar, and cruciate ligaments, articular capsule, and synovial membrane (13). Another typical CT finding is the combination of subchondral cysts and erosion in the OP (19), similar to our case.

Jain et al. (19) concluded that the retro-odontoid pseudotumor in case of crystal deposition appears hypointense to marrow signal on both T1- and T2-weighted images, compressing the odontoid. There may be further degenerative changes such as sclerosis, osteophytosis, and subluxation (19).

Grob et al. (5) described four grades of pannus: grade 1, little/no pannus; grade 2, moderate pannus; grade 3, massive pannus, without spinal cord compression; grade 4, massive pannus with spinal cord or brain stem compression. In our case, the patient had a grade 4 pannus.

Different types of pannus have been classified in the literature such as hypervascular, hypovascular, and fibrous pannus (1).

Pathophysiology of Calcium Pyrophosphate Dihydrate Deposition Disease

Many authors (7, 20) presented that the pathomechanism of CPPD crystal formation in the articular fibrocartilaginous structures has not been completely understood yet. Several pathophysiological theories exist about CPPD. CPPD may result from an imbalance between the production of pyrophoshate and the level of pyrophosphatases in the diseased cartilage (21). Pyrophosphate deposits in the synovium may combine with calcium to form CPP crystals (7). The formation of CPP crystals in the pericellular matrix of the cartilage is the first step in the disease process (7), but chondrocytes appear to play an important role.

Chondrocytes generate "pericellular exosome-sized vesicles," also termed as "articular cartilage vesicles," which are one of the important sites of crystal formation in cartilage; furthermore, they produce extracellular inorganic phosphates, which are essential to the formation of CPP crystals (7).

Zünkeler et al. (20) hypothesized that fibroblast in the cervical spine ligament transforms into chondrocyte and that the transformation causes calcification. Furthermore, they postulated that mechanical trauma may be the initial event that affect crystal formation.

Once located in the joint, CPP crystals may contribute to further mechanical damage (by altering the mechanical properties of the cartilage (7)) of the adjacent joint tissue and initiate an inflammatory process by activating components of the NLRP3 inflammasome and by creating neutrophil extracellular traps (7), as suggested by experimental studies in which CPP crystals were injected into the synovial space (20, 22).

Moreover, a number of comorbidities correlate with CPPD (21). Different studies demonstrated that hyperparathyroidism presented the highest positive association with CPPD, followed by gout, osteoarthritis, rheumatoid arthritis, and hemochromatosis (21). Beside these comorbidities, hypomagnesemia, osteoporosis, chronic kidney disease, calcium supplementation (21), and Wilson's disease (20, 23) appear to be related.

Conservative Treatment Options of CDS

Most authors have recommended treatment with NSAIDs and/or steroids (especially prednisolone) (13, 24, 25). Oka et al. (17) summarized in their review that 85% of the patients with CDS were treated with NSAID alone or NSAID with another drug. In most of the cases, the clinical symptoms improve within 4–7 days (11, 13, 26).

Lee et al. (13) pointed out that after the initial improvement within 1 week, there is a slow but persistent improvement in 3–5 weeks.

Oka et al. (17) reported that 67.5% of patients with CDS were treated with NSAID alone, 15% with steroids alone, 7.5% with NSAIDs and steroids, 5% with NSAID and tizanideine, 2.5% with NSAID, colchicine, and steroid, and 2.5% with NSAID and carbamazine.

Different authors (7, 17) also presented the use of magnesium, iron chelators, probenecid, and phosphocitrate for the treatment of associated metabolic conditions in patients with CPPD (especially to inhibit crystal formation) and colchicine, methotrexate, and hydroxychloroquine to prevent the inflammasome activation. Treatment with interleukin-1 (IL-1) inhibitor is possible (e.g., anakinra, canakinumab, IL-1 trap).

Jain et al. (19) advocated the use of NSAIDs and colchicine and mentioned that patients show dramatic improved during this treatment.

As shown in the present case and in some cases, treatment of pannus by conservative methods may take months. During this time, the patient is already at a high risk of further impairment, especially in the presence of brainstem compression.

Surgical Treatment of CDS

Even if conservative therapy is indicated in most cases of CDS, surgery is also indicated in a few cases (27). Fiani et al. (4) concluded that occipital–cervical fusion "is indicated in cases where the panni impinge on the medulla and the upper cervical cord" and that the "goal in occipital surgical fusion is to prevent further progression of the pseudotumor and improve neurological outcomes." Furthermore, they concluded that "neurological improvements are often noted in patients as soon as 1 week after surgery and complete resolution of the pseudotumor can be visualized on imaging within 1 year of surgical repair."

Baysal et al. (28) reported that among 17 patients of CDS who progressively presented neurological symptoms, one patient was treated by decompression surgery. Zünkeler et al. (20) performed surgery in six of seven patients with periodontoid CPPD disease, and most of them even underwent two surgical sessions: first with the transoral–transpharyngeal approach and second with the posterior fusion of C0–C2.

According to most authors and to our opinion, surgery is necessary in case of massive brainstem compression, myelopathy, dramatic progression of neurological symptoms, unclear diagnosis (e.g., in case of DD metastases) and instability. In our case, the patient had a massive brainstem compression and displacement and progressive walking impairment. Therefore, surgery was performed.

PESCA might be a good alternative and is easier to perform in periodontoid lesions than in odontoid lesions because the trajectory is not as deep. Even if the window of PESCA is small, the surgical path is narrow, and the working angle is oriented up, performing surgery in one session is a huge advantage for the patient (16). To best of our knowledge this is the first case of CDS which had been managed by this concept.

Craniocervical Junction Abnormalities in Saethre-Chotzen Syndrome

In this report, the patient had SCS, which is a craniosynostosis syndrome that arises in 1 per 100,000 live births (29). It presents as low hairline, ptosis, external ear abnormalities, tear duct stenosis, hand anomalies, and short statute. Clinical diagnosis in these patients is usually genetically confirmed by a deletion of mutation in the *TWIST1* gene (29).

Cervical spinal changes have been described in SCS. Anderson et al. (30) and Trusen et al. (31) reported that fusion of vertebral bodies and/or posterior elements may occur in the cervical spine.

Lateral and Posterior Approaches to OP

Riley et al. (32) concluded that there are three approaches to the OP: 1. Anterior, 2. Lateral and 3. Posterior.

Beside anterior approaches (such as transoral, endoscopic endonasal, anterior high retrophayryngeal and transcervical approaches) (32, 33) several authors have advocated for the lateral and for the posterior approaches:

A number of authors (34–36) described the (far lateral) transcondylar approach, the trans-atlas extradural approach, the extreme lateral-transatlas approach (37), and the extreme lateral trans-odontoid (ELTO)[35] used in the removal of OP, retro-odontoid lesions (such as synovial cysts) or extending lesions in and around the OP (such as chordomas).

One risk of transcondylar and trans-atlas approaches is instability (37). Another risk of transcondylar approach is injury of hypoglossal nerve due to proximity in its location (38, 39). On the-other-hand trans-atlas approach includes the risk of injury of the VA (37).

Oya et al. (40) described an approach with skin incision on the posterior margin of the sternocleidomastoid muscle. Then, they cut a reflection of the SCM to be inserted in the

posterior space of the SCM muscle, transverse process of C1, C2, and C3, in order for odontoidectomy to be carried out. Naito et al. (41) published the high cervical lateral approach through retroauricular curved skin incision for removal of retro-odontoid pseudotumors.

Srivastava et al. (42) described a simultaneous odontoid excision with bilateral posterior C1-2 distraction and stabilization utilizing bilateral posterolateral corridors and a single posterior midline incision. Grundy et Gill described an approach to OP through a midline incision from the external occipital protuberance to the spinous process of C6, and a transverse occipital incision (T-Incision). The posterior arch of C1 was removed as well as the pedicle of C1 and posterior boundary of the vertebral canal.

The posteriolateral transpedicular approach to C2 has a narrow trajectory (because of the diameter and angle of the pedicles); therefore, the reachable targets are limited and in most cases, the upper part of the OP is not reachable. This approach has been used mainly for biopsy.

Riley et al. (32) advocated for the METRx posterolateral approach, which uses a paravertebral incision and they entered a METRx dilatator for a minimal invasive surgical approach to OP. Eissa and Eldin (43) analyzed an approach in which they performed a midline skin incision on cadavers and extended it laterally (as inverted L) to help the lateral dissection and exposure of the vertebral artery. A C2 neurectomy was perfomed with exposure of the C2 *pars interarticularis* and the inferior articular atlas was used as a guide to expose the atlanto-occipital joint ways. Mobilization of VA could be necessary to enlarge the surgical window (44).

The most posterior approach is the transdural approach (45, 46) which has a high risk of cerebrospinal fluid leakage and infection. Furthermore, in the case of a tumor or infection, the dura mater (a natural barrier) is opened and may lead to intradural insertion of the pathology.

Main advantage of posteriolateral approaches is that occipitocervical fixation and decompression can be performed in same sitting (16).

In our case we used PESCA (16) which uses a midline incision in combination with previous decompression, thereby enlarging the foramen of magnum and medial C1 removal. The lateral corridor between the lateral part of C1 arch and the lateral part of C2 arch is enlarged by drilling of the inferior lateral part of the C1 arch and the lateral superior part of C2 arch. The condyles and the atlas were not removed.

CONCLUSION

In summary, CDS is a rare disease that usually can be treated conservatively. In cases of brainstem compression, brainstem displacement, or neurological impairment, surgery should be discussed to prevent further worsening of neurological symptoms or even death.

To best of our knowledge, SCS and CDS in the same patient have not been described yet. A correlation of CDS and SCS has been not described in literature. This study demonstrates that PESCA can be used to obtain tissue for pathological analysis in one surgical sitting after fusion and decompression and that fusion, decompression, and PESCA (in the same session) together with subsequent conservative management could be a good alternative for the treatment of CDS.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics Committee of the University Hospital Tübingen, Germany; reference number 478/2020BO. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

PH: performed analyses, performed 3D-print, and critical revision. T-KH, KK, MS, and MT: performed analyses and critical revision. SA: idea and development of PESCA, performed surgery, performed analyses, wrote the article, and critical revision. All authors listed have made substantial, direct, and intellectual contribution to the work and approved it for publications.

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REFERENCES

1. Shi J, Ermann J, Weissman BN, Smith SE, Mandell JC. Thinking beyond pannus: a review of retro-odontoid pseudotumor due to rheumatoid and non-rheumatoid etiologies. *Skeletal Radiol.* (2019) 48:1511–23. doi: 10.1007/s00256-019-03187-z
2. Joyce AA, Williams JN, Shi J, Mandell JC, Isaac Z, Ermann J. Atlanto-axial pannus in patients with and without Rheumatoid Arthritis. *J Rheumatol.* (2019) 46:1431–7. doi: 10.3899/jrheum.181429
3. Zvaifler NJ, Firestein GS. Pannus and pannocytes. Alternative models of joint destruction in rheumatoid arthritis. *Arthritis Rheum.* (1994) 37:783–9. doi: 10.1002/art.1780370601
4. Fiani B, Houston R, Siddiqi I, Arshad M, Reardon T, Gilliland B, et al. Retro-Odontoid Pseudotumor formation in the context of various acquired and congenital pathologies of the craniovertebral junction and surgical techniques. *Neurospine.* (2021) 18:67–78. doi: 10.14245/ns.2040402.201
5. Grob D, Würsch R, Grauer W, Sturzenegger J, Dvorak J. Atlantoaxial fusion and retrodental pannus in rheumatoid arthritis. *Spine.* (1997) 22:1580–3. doi: 10.1097/00007632-199707150-00010

6. Koyfman A, Yaffe D. Crowned dens syndrome. A case report. *Neuroradiol J.* (2014) 27:495–7. doi: 10.15274/NRJ-2014-10056
7. Rosenthal AK, Ryan LM. Calcium pyrophosphate deposition disease. *N Engl J Med.* (2016) 374:2575–84. doi: 10.1056/NEJMra1511117
8. Garcia GM, McCord GC, Kumar R. Hydroxyapatite crystal deposition disease. *Semin Musculoskelet Radiol.* (2003) 7:187–93. doi: 10.1055/s-2003-43229
9. Bouvet JP, le Parc JM, Michalski B, Benlahrache C, Auquier L. Acute neck pain due to calcifications surrounding the odontoid process: the crowned dens syndrome. *Arthritis Rheum.* (1985) 28:1417–20. doi: 10.1002/art.1780281215
10. Sato Y, Yasuda T, Konno S, Kuwayama A, Komatsu K. Pseudogout showing meningoencephalitic symptoms: crowned dens syndrome. *Intern Med.* (2004) 43:865–8. doi: 10.2169/internalmedicine.43.865
11. Ziza JM, Bouvet JP, Auquier L. [Acute suboccipital neck pain of calcifying origin]. *Rev Rhum Mal Osteoartic.* (1982) 49:549–51.
12. Goto S, Umehara J, Aizawa T, Kokubun S. Crowned dens syndrome. *J Bone Joint Surg Am.* (2007) 89:2732–6. doi: 10.2106/JBJS.F.01322
13. Lee GS, Kim RS, Park HK, Chang JC. Crowned dens syndrome: a case report and review of the literature. *Korean J Spine.* (2014) 11:15–7. doi: 10.14245/kjs.2014.11.1.15
14. Tang J, Li J, Wu C, Li Y, Lu Q, Xie W, et al. Report of four cases of crowned dens syndrome: clinical presentation, CT findings and treatment. *Exp Ther Med.* (2020) 20:3853–9. doi: 10.3892/etm.2020.9128
15. Uh M, Dewar C, Spouge D, Blocka K. Crowned dens syndrome: a rare cause of acute neck pain. *Clin Rheumatol.* (2013) 32:711–4. doi: 10.1007/s10067-013-2179-5
16. Haas P, Hauser T-K, Kandilaris K, Schenk S, Tatagiba M, Adib SD. Posterolateral epidural supra-C2-root approach (PESCA) for biopsy of lesions of the odontoid process in same sitting after occipitocervical fixation and decompression-perioperative management and how to avoid vertebral artery injury. *Neurosurg Rev.* (2021) 44:2947–56. doi: 10.1007/s10143-020-01468-z
17. Oka A, Okazaki K, Takeno A, Kumanomido S, Kusunoki R, Sato S, et al. Crowned dens syndrome: report of three cases and a review of the literature. *J Emerg Med.* (2015) 49:e9–e13. doi: 10.1016/j.jemermed.2015.02.005
18. Aouba A, Vuillemin-Bodaghi V, Mutschler C, De Bandt M. Crowned dens syndrome misdiagnosed as polymyalgia rheumatica, giant cell arteritis, meningitis or spondylitis: an analysis of eight cases. *Rheumatology.* (2004) 43:1508–12. doi: 10.1093/rheumatology/keh370
19. Jain N, Verma R, Garga UC, Baruah BP, Jain SK, Bhaskar SN, et al. and MR imaging of odontoid abnormalities: a pictorial review. *Indian J Radiol Imaging.* (2016) 26:108–19. doi: 10.4103/0971-3026.178358
20. Zünkeler B, Schelper R, Menezes AH. Periodontoid calcium pyrophosphate dihydrate deposition disease: "pseudogout" mass lesions of the craniocervical junction. *J Neurosurg.* (1996) 85:803–9. doi: 10.3171/jns.1996.85.5.0803
21. Zamora EA, Naik R. "Calcium Pyrophosphate Deposition Disease," in *StatPearls* (Treasure Island (FL): StatPearls Publishing). Available online at: http://www.ncbi.nlm.nih.gov/books/NBK540151/ (accessed May 16, 2021).
22. Fam AG, Morava-Protzner I, Purcell C, Young BD, Bunting PS, Lewis AJ. Acceleration of experimental lapine osteoarthritis by calcium pyrophosphate microcrystalline synovitis. *Arthritis Rheum.* (1995) 38:201–10. doi: 10.1002/art.1780380208
23. Doherty M, Dieppe P. Clinical aspects of calcium pyrophosphate dihydrate crystal deposition. *Rheum Dis Clin North Am.* (1988) 14:395–414. doi: 10.1016/S0889-857X(21)00972-8
24. Godfrin-Valnet M, Godfrin G, Godard J, Prati C, Toussirot E, Michel F, et al. Eighteen cases of crowned dens syndrome: presentation and diagnosis. *Neurochirurgie.* (2013) 59:115–20. doi: 10.1016/j.neuchi.2013.03.003
25. Ojemolon PE, Edigin E, Annapureddy N, Manadan A, A. Case of acute neck pain: the crowned dens syndrome. *Cureus.* (2020) 12:e9555. doi: 10.7759/cureus.9555
26. Resnick D, Pineda C. Vertebral involvement in calcium pyrophosphate dihydrate crystal deposition disease. Radiographic-pathological correlation. *Radiology.* (1984) 153:55–60. doi: 10.1148/radiology.153.1.6089266
27. Klineberg E, Bui T, Schlenk R, Lieberman I. Retro-odontoid calcium pyrophosphate dehydrate deposition: surgical management and review of the literature. *Evid Based Spine Care J.* (2014) 5:63–9. doi: 10.1055/s-0034-1370897
28. Baysal T, Baysal O, Kutlu R, Karaman I, Mizrak B. The crowned dens syndrome: a rare form of calcium pyrophosphate deposition disease. *Eur Radiol.* (2000) 10:1003–5. doi: 10.1007/s003300051052
29. Den Ottelander BK, Van Veelen MC, De Goederen R, Van De Beeten SD, Dremmen MH, Loudon SE, et al. Saethre–Chotzen syndrome: long-term outcome of a syndrome-specific management protocol. *Dev Med Child Neurol.* (2021) 63:104–10. doi: 10.1111/dmcn.14670
30. Anderson PJ, Hall CM, Evans RD, Hayward RD, Harkness WJ, Jones BM. The cervical spine in Saethre-Chotzen syndrome. *Cleft Palate Craniofac J.* (1997) 34:79–82. doi: 10.1597/1545-1569_1997_034_0079_tcsisc_2.3.co_2
31. Trusen A, Beissert M, Collmann H, Darge K. The pattern of skeletal anomalies in the cervical spine, hands and feet in patients with Saethre-Chotzen syndrome and Muenke-type mutation. *Pediatr Radiol.* (2003) 33:168–72. doi: 10.1007/s00247-002-0823-3
32. Riley K, Singh H, Meyer SA, Jenkins AL. Minimally invasive surgical approach for odontoid lesions: a technical description in a case of high cervical osteomyelitis and abscess. *World Neurosurg.* (2016) 91:332–9. doi: 10.1016/j.wneu.2016.04.028
33. Visocchi M, Signorelli F, Liao C, Rigante M, Paludetti G, Barbagallo G, et al. Transoral vs. transnasal approach for craniovertebral junction pathologies: never say never. *World Neurosurg.* (2018) 110:592–603. doi: 10.1016/j.wneu.2017.05.125
34. Adada B, Vera Silva MA, Darwish H, Dakwar E. Far-lateral trans-atlas extradural resection of retro-odontoid synovial cyst: surgical technique and review of literature. *Interdisc Neurosurg.* (2019) 17:28–35. doi: 10.1016/j.inat.2019.01.018
35. Alzhrani G, Gozal YM, Eli I, Sivakumar W, Raheja A, Brockmeyer DL, et al. Extreme lateral transodontoid approach to the ventral craniocervical junction: cadaveric dissection and case illustrations. *J Neurosurg.* (2018) 131:920–30. doi: 10.3171/2018.4.JNS172935
36. Dowd GC, Zeiller S, Awasthi D. Far lateral transcondylar approach: dimensional anatomy. *Neurosurgery.* (1999) 45:95–9. doi: 10.1097/00006123-199907000-00023
37. Türe U, Pamir MN. Extreme lateral-transatlas approach for resection of the dens of the axis. *J Neurosurg.* (2002) 96:73–82. doi: 10.3171/spi.2002.96.1.0073
38. al-Mefty O, Borba LA, Aoki N, Angtuaco E, Pait TG. The transcondylar approach to extradural non-neoplastic lesions of the craniovertebral junction. *J Neurosurg.* (1996) 84:1–6 doi: 10.3171/jns.1996.84.1.0001
39. Sen CN, Sekhar LN. Surgical management of anteriorly placed lesions at the craniocervical junction–an alternative approach. *Acta Neurochir (Wien).* (1991) 108:70–7. doi: 10.1007/BF01407670
40. Oya S, Tsutsumi K, Shigeno T, Takahashi H. Posterolateral odontoidectomy for irreducible atlantoaxial dislocation: a technical case report. *Spine J.* (2004) 4:591–4. doi: 10.1016/j.spinee.2004.01.013
41. Naito K, Yamagata T, Kawahara S, Ohata K, Takami T. High cervical lateral approach to safely remove the cystic retro-odontoid pseudotumor: technical note. *Neurol Med Chir.* (2019) 59:392–7. doi: 10.2176/nmc.tn.2019-0060
42. Srivastava AK, Behari S, Sardhara J, Das KK. Simultaneous odontoid excision with bilateral posterior C1-2 distraction and stabilization utilizing bilateral posterolateral corridors and a single posterior midline incision. *Neurol India.* (2017) 65:1068–75. doi: 10.4103/neuroindia.NI_819_17
43. Eissa EM, Eldin MM. Odontoidectomy through posterior midline approach followed by same sitting occipitocervical fixation: a cadaveric study. *J Craniovertebr Junction Spine.* (2017) 8:58–63. doi: 10.4103/0974-8237.199879
44. George B, Laurian C. Surgical approach to the whole length of the vertebral artery with special reference to the third portion. *Acta Neurochir.* (1980) 51:259–72. doi: 10.1007/BF01406753
45. Archer J, Thatikunta M, Jea A. Posterior transdural approach for odontoidectomy in a child: case report. *J Neurosurg: Pediat.* (2020) 25:8–12. doi: 10.3171/2019.7.PEDS19337

46. Fujiwara Y, Manabe H, Sumida T, Tanaka N, Hamasaki T. microscopic posterior transdural resection of cervical retro-odontoid pseudotumors. *J Spinal Disord Tech.* (2015) 28:363–9. doi: 10.1097/BSD.0000000000000335

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Predictors of Complications and Unfavorable Outcomes of Minimally Invasive Surgery Treatment in Elderly Patients With Degenerative Lumbar Spine Pathologies (Case Series)

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Introduction: The use of minimally invasive surgery (MIS) results in fewer adverse and more improved outcomes. However, the literature data describing the factors increasing the number of complications, reoperation frequency and unscheduled re-hospitalizations in older patients after MIS are contradictory. In this study, a large number of patients was investigated for the complications of minimally invasive surgical treatment of degenerative disease of the lumbar spine in older patients. The objective of the study was to determine the predictors of unfavorable outcomes in such patients.

Materials and Methods: 1,013 patients underwent MIS (decompression alone, TLIF, LLIF, ALIF) in 2013-2017. All operations were performed with the participation of the authors (neurosurgeons). The patient's average age was 66. The following data were collected: BMI; CCI; presence of postoperative complications according to the Dindo-Clavien classification; unplanned readmission at 90 days; hospital length of stay (LOS); surgical complexity (low, intermediate, and high); surgical time; and risk factors. The cumulative reoperation rate was determined at 5-years follow-up.

Results: A total of 256 patients suffered a complication (25.2%), 226 classified as mild (grade I, II, IIIA), and 30 - as severe (IIIB, IVA). Such factors as the surgical complexity, BMI $>$ 30, surgical time, number of operated levels were associated with a significant risk of developing a complication. For patients with and without complications, LOS was 9.3 and 6.3 days, respectively ($p < 0.0001$), the unplanned readmission rate was 1.3%. 104 patients underwent 133 revision operations. The 5-year cumulative reoperation rate was 15.2%, and the reoperation index was 12.1%. The CCI had no statistically significant effect on the complication incidence after MIS. A higher risk of complications was found in patients who underwent intermediate-complexity surgery (MIS TLIF) compared with uncompounded (decompression alone) and more complex (MIS LLIF, MIS ALIF) surgical procedures ($p < 0.001$ and $p = 0.001$, respectively).

Conclusion: A register of postoperative complications is an important tool for health quality assessment and choosing the best surgical option that helps to establish measures to reduce such complications. Using MIS for the treatment of elderly patients reduces the number of severe complications.

Keywords: lumbar spine, degenerative disorders, minimally invasive surgery, complications, elderly patients, case series

INTRODUCTION

The problem of improving quality of life for elderly and geriatric patients with degenerative lumbar spine pathologies of is a matter of ongoing scientific research that still remains unresolved. The relevance of the issue is explained by increasing life expectancy, advancements in diagnostics of this complex disease, availability of new data on its etiology and pathogenesis, and scientific and technical progress leading to the development of new surgical options (1). The complexity of the issue rises from the nosological diversity of degenerative pathology; the possibility of multiple and multilevel degenerative changes in the spine; the non-homogeneity of the elderly patient population, and the somatic comorbidities (2). Most patients have excess body mass, reduced bone tissue mineral density, comorbidity burden, and various degrees of sagittal imbalance of the vertebral column with respective compensatory mechanisms. All these factors make it difficult to come up with unified assessment criteria and identify an optimal surgical treatment. Surgical interventions come with risks of intraoperative and postoperative complications, the complication rate naturally increasing with age and the presence of a concomitant pathology. However, the literature data on complication predictors are contradictory (3–8). Several papers dedicated to identifying predictors of unfavorable surgical outcomes in elderly patients with degenerative LSS are available, but the conclusions regarding the effect of obesity, concomitant pathology, and psychological status of patients turn out to be ambiguous (9–13). Evidence-based studies are available showing an increase in complication rate in elderly and geriatric patients receiving surgical treatment of longer duration (14). Some authors call for using maximum clinical efficacy to identify the indications, restrictions, and extent of surgical treatment (4). Others note the high success rate of surgical treatment after using fixation hardware in elderly patients (15).

Ambiguous long-term results of surgical treatment in this age group call for further study and multi-aspect assessment. Thus, the objective of the present paper was to study predictors of complications and unfavorable outcomes after minimally invasive surgical (MIS) treatment of degenerative lumbar spine pathology in elderly patients.

MATERIALS AND METHODS

Retrospective analysis of the effect of concomitant medical conditions, including obesity and osteoporosis, in a consecutive case series of 1,013 elderly and geriatric patients (WHO classification of 1963) operated for degenerative lumbar spine pathology was performed at single-center Federal Neurosurgical Center (Novosibirsk, Russia). The data were collected from December 1, 2013 to December 31, 2017. The analysis included 367 (36%) male and 646 (64%) female patients, the average age being 66 years [66/65 (62;69) years]. Here and below, the data format is as follows: mean/median (quartile 1; 3).

Inclusion Criteria

1) Elderly and geriatric age under the WHO classification of 1963;
2) Degenerative changes in the lumbar spine, the cause(s) being as follows:
   - Disc herniation and/or spinal canal stenosis;
   - Segmental instability and/or spinal deformity in sagittal (low grade (Meyerding grade 1–2) degenerative spondylolisthesis) (16) and frontal (Cobb angles of $>10^{\circ}$ and $\leq 30^{\circ}$) planes;
   - Respective clinical manifestations in the form of intermittent neurogenic claudication, radiculopathy or both combined or persistent spinal pain syndrome in the form of chronic pains in the lumbar spine (VAS score of 5 or above);
3) No positive effect from combined conservative therapy for 12 weeks;
4) Minimally invasive surgical treatment of degenerative disease (MIS).

The patients with idiopathic scoliosis, degenerative scoliosis in the lumbar spine with a Cobb angle of over 30°, and the patients with previous history of spinal surgery were not included in the analysis. Exclusion criteria also included spinal tumors and inflammatory lesions, decompensated somatic pathology, and intermittent claudication of vascular origin.

The 1,013 patients were operated minimally invasive techniques (decompression alone, TLIF, LLIF, ALIF) in 2013–2017.

Assessment Methods and Criteria

Taking into account the age of the patients, a complete standard examination was performed in the outpatient setting to discover somatic comorbidities, and the patients received the respective treatment, if necessary. A preoperative neurological clinical examination consisting of X-ray imaging of all spinal regions in standard views with frontal and sagittal balance assessment, an intrathecal contrast-enhanced CT scan of the lumbar spine, and an MRI scan was performed. At *T*-values below −2.5A, a mandatory DXA scan of the lumbar spine and proximal

thigh was performed, and bone cement injection was added to screw fixation.

Lumbar spine radiography with functional tests (maximum flexion and extension) was performed to describe segmental biomechanics as follows: vertebral displacement in the neutral position, sagittal translation and angulation. Vertebral displacement was measured according to White and Panjabi (17).

A lumbar spine MRI scan was performed for all patients to evaluate degenerative changes in the intervertebral discs. Post-operative MRI scans were performed, when patients showed signs of complications as follows: CSF leak, epidural hematoma, residual nerve root compression, early and late disc reherniation, and surgical site infection.

A spiral CT scan (SCT) with intrathecal contrast enhancement (omnipaque 300, 10 ml) and with further MPR and 3D VRT reconstruction was also performed for all patients to specify the stenotic region. Screw malposition was evaluated according to Rao et al. (18).

The Charlson Comorbidity Index (CCI) (19) reflecting a 10-year survival rate in patients with concomitant somatic pathology adjusted for age was calculated to evaluate the somatic status and concomitant somatic pathology (20).

The effect obesity and concomitant somatic pathologies had on the quality of life, functional status, and pain syndrome was analyzed taking into account surgical time (min), intraoperative blood loss (ml), hospital length of stay (bed-day), early and late postoperative complications (21).

The VAS score was used to evaluate pain intensity (in legs and back) before and after the operation and also at 12 and 24 months after each operation. The Oswestry Disability Index (ODI) and SF36 form were used to evaluate the functional activity and quality of life in patients (PH is physical health and MH is mental health) before the operation, at 12 and 24 months after the operation, and during future visits. Changes were evaluated based on MCID (22).

The clinical effectiveness of the surgical treatment was evaluated in the form of an in-person or a phone survey. The patients were invited for in-person orthopedic and neurological examination or inpatient examination, if necessary. 748 (74%) patients underwent follow-up examination. The other patients either did not answer the phone call or refused to come to examination due to living too faraway.

Complications were evaluated based on the Dindo-Clavien classification (2004) (23) validated for lumbar spine surgery (24).

Assessment of Long-Term Results

Vertical X-rays and CT scans from the early postoperative period were used to specify the positions of hardware elements. Plain and functional X-rays and CT scans performed at 3, 6, and 12 months after the operation were used to control the hardware positions and identify instability in the operated and adjacent segments. Bone block formation according to Tan (presence at Grades 1–2 and absence at Grades 3–4) (25) was evaluated based on CT scans at 12 months after the operation. After that, X-ray imaging and CT scans were performed, if necessary.

Cumulative reoperation rate. This parameter was calculated for a 5-year period as the sum of yearly reoperation rates in patients with sufficient follow-up period (here, $n = 5$):

$$I_n = \sum_{i=1}^{n} \frac{Number\ of\ reoperations\ at\ the\ i-th\ year\ after\ a\ primary\ procedure}{Number\ of\ patients\ followed-up\ for\ at\ least\ i\ years}, \%.$$

The reoperation frequency index for n years was calculated similarly as the sum of yearly numbers of reoperated patients for patients with sufficient follow-up period (26).

$$P_n = \sum_{i=1}^{n} \frac{Number\ of\ the\ first\ reoperations\ at\ the\ i-th\ year}{Number\ of\ patients\ followed-up\ for\ at\ least\ i\ years}, \%.$$

Generally, the reoperation frequency $\leq$ the cumulative reoperation rate.

Clinical and Radiographic Description of the Patient Cohort

The main reason for the patients to seek for medical help was neurological compression syndromes and persistent spinal pain syndrome. The leg-pain VAS scores were 6.7/7 (5; 8). The spine pains with VAS scores of 6.1/6 (5; 8) had a significant functional and quality-of-life impact with a mean ODI score of 56.2/57 (44; 66), SF-36 PH score of 26.6/26 (23; 30), and SF-36 MH score of 27.9/27 (22; 33). Leg pains prevailed over back pains in 406 (40%) patients. Back pains prevailed in 262 (26 %) patients, of which 29 identified a spinal pain syndrome with leg-pain VAS score not exceeding 2 as the only quality of life impact. The same pain intensity in the legs and back was observed in 345 (34%) patients.

Neurological clinical examination showed radiculopathy in 665 (68%) patients with leg- pain VAS score of 7/7 (6; 8). Intermittent neurogenic claudication was observed in 319 (31%) patients with walking distances of 96/100 (50; 100) m. Most patients (883 (87%) had single-level lumbar spine stenosis; clinically significant spinal canal stenosis at two levels was identified in 108 (11%) patients and at three levels in 22 (2%) patients.

Neuroimaging showed degenerative spondylolisthesis in 428 (42%) patients, of which 390 (91%) were grade 1 cases, and 38 (9%)—grade 2 cases, according to Meyerding (16). In addition, there were 81 (12.8%) cases, where degenerative spondylolisthesis was not accompanied by segmental instability, i.e., the score was below 5, according to A. A. White and M. M. Panjabi (17). The scores of 5 and above corresponding to clinical segmental instability were observed in 338 patients (33% of the total cohort size). The instability was accompanied by radiculopathy, intermittent neurogenic claudication or both in 317 patients (93.8% of 338). It involved a single segment in 307 (90.8%) cases, two segments in 30 (8.9%) cases, and three segments in 1 (0.3%) case. A pathology in the apical segment of lumbar lordosis at L4-L5 observed in 243 patients (71.9%) was the most common with

a mean score of 6.3/6 (6; 7), according to A. A. White and M. M. Panjabi.

Clinically significant spinal canal stenosis without segmental instability was considered an indication for neurovascular structures decompression (27).

A total of 365 microsurgical discectomies were performed, of which 356 were at a single level, 8—at two levels, and 1—at three levels. Microsurgical decompression using the modified Wiltse approach was performed in 28 cases. A total of 86 unilateral microsurgical decompressions of lateral recess were performed in patients with lateral stenosis, of which 83 were at a single level and 3—at two levels. Lateral recess decompression was combined with microsurgical discectomy in 23 patients. Over-the-top microsurgical decompression was performed in 145 patients with clinical and radiographic signs of central canal stenosis.

Stabilization surgery (28) was performed in patients with segmental instability according to White and Panjabi (17). MIS TLIF with direct over-the-top decompression and transpedicular fixation (TPF) was performed in 142 out of 163 central canal stenosis cases, and indirect decompression (ALIF/LLIF)—in 21 cases. MIS TLIF with direct microsurgical decompression was performed in all patients with clinically significant lateral canal stenosis ($n = 103$) (29). MIS TLIF was performed in 40 out of 51 patients with foraminal stenosis, and ALIF/LLIF in 11 patients. MIS TLIF was used for surgical treatment of instability in 294 patients, ALIF—in 23 patients, and LLIF—in 21 patients. Operations were performed at a single level in 307 cases, on two levels—in 30 cases, and at three levels—in 1 case. All multilevel surgical procedures were MIS TLIF operations.

Degenerative scoliosis of the lumbar spine with a Cobb angle of 10–30° in the frontal plane was diagnosed in 91 (9%) patients. Only 51 patients from the studied cohort or 5% of the total cohort size received two-stage corrective operations with two MIS techniques (LLIF and MIS TPF) performed in one surgical session. Among those, 44 patients (86%) were female, and 7 patients (14%) were male. The mean age was 67/67 (63; 70) years (from 60 to 81 years). All these patients had a disability with an ODI score of 56/54 (45; 62) accompanied by quality-of-life deterioration on the SF-36 scale [PH score of 25/24 (22; 28), MH score of 26/26 (22; 28)]. The Cobb angle for the group was 16.5/15 (11; 20°). Patients suffered from spinal pain syndrome with a spine-pain VAS score of 6.6/6 (5; 8) and various compression syndromes [84% or 43 patients in the third group had a leg-pain VAS score of 6.3/6 (5; 8)]. All patients complained about the inability to stand upright for a long time and walking impairments due to difficulty in maintaining vertical position as a result of local or global sagittal balance impairment. Pain syndrome was caused by degenerative scoliosis in the lumbar spine [mean Cobb angle of 16.5/15 (11; 20°)]. All patients from this group had an N curve as per the SRS-Schwab classification. All patients had sagittal balance impairments with excessive sagittal modifier values. Neuroimaging showed that 35 patients from the third group (68.6%) had degenerative scoliosis combined with degenerative spondylolisthesis at one (9), two (23), or three levels (3). Among those, 34 were a Meyerding grade 1 case, and one—a grade 2 case. The remaining 40 patients (4%) received decompressive surgery or decompression with spine stabilization depending on the prevalent clinical symptoms.

Most patients had excess body mass (30), with 327 (32%) patients having BMI above the normal threshold of 25 but below 30 ($25 \leq \text{BMI} < 30$). Class 1 obesity ($30 \leq \text{BMI} < 35$) was observed in 322 (32%) patients, class 2 obesity ($35 \leq \text{BMI} < 40$)—in 181 (18%) patients, and class 3 obesity ($\text{BMI} > 40$)—in 79 (8%) patients.

Somatic comorbidity was discovered in 999 (98.6%) patients: 155 patients (15.5% from 999) had an isolated pathology, while the vast majority of 843 patients (84.5% from 999) had a concomitant pathology. Gastrointestinal and cardiovascular pathologies were the most common. The mean CCI value in the studied cohort was 63/77 (53; 90%).

Statistical Analysis

The normal distribution hypothesis for quantitative values was tested using the Kolmogorov–Smirnov and Shapiro–Wilk tests. Since most quantitative and scale data were not normally distributed, nonparametric criteria were used in the calculations. In the present paper, the numerical data format is as follows: mean/median (quartile 25; 75%).

The correlations between values and their strengths were estimated using Spearman's correlation coefficient. The two-sided Mann–Whitney test was used to compare two independent samples by quantitative values, and the Kruskal–Wallis test—for three samples. To compare the studied groups by qualitative values, Fisher's exact test or its asymptotic version (for contingency table dimensions above 2×2) was applied.

To isolate complication predictors, a logistic regression model with a stepwise algorithm for predictor inclusion/exclusion was used. The prediction adequacy hypothesis was tested using the Hosmer–Lemeshow test. R software was used for statistical data processing (31).

This case series has been reported in line with the PROCESS Guideline (32).

RESULTS

The surgical procedures ($n = 1{,}146$) were divided into three types 3 based on surgical injury and extent of operation:

Patients from the first group ($n = 624$) underwent low-complexity operations, such as microsurgical discectomy, lateral recess decompression, central canal decompression, including both single-level and multilevel operations. The low-complexity group included 624 patients (61.6% of the total cohort size): 277 males (44.4%) and 347 females (55.6%) aged 60–88 years [67/65 (62; 70)]. A total of 710 operations were performed, including 86 reoperations.

Patients from the second group ($n = 338$) underwent intermediate-complexity operations, such as direct decompression with spinal fusion and fixation (mostly at 1 and 2 levels with one operation at three levels). This group included 338 patients (33% of the total cohort size): 83 males (24.6%) and 255 females (75.4%) aged 60–86 years [66/65 (62; 68)]. The patients from the second group underwent a total of 379 operations, including 41 reoperations.

TABLE 1 | Quality-of-life assessment in patients from the first group (*marks statistically significant changes ($p < 0.05$) compared to preoperative values).

Parameters	Pre-op (624)	Up to 1 year (245)	Over 1 year (262)
Group 1 ODI	55/56 (42; 68)	27/27 (14; 38)*	18/13 (4; 29)*
Patients with ↓ ODI of at least 12.8 (22)	—	166	206
SF-36 PH	27/26 (23; 30)	40/39 (32; 47)*	43/46 (36; 52)*
Patients with ↑ SF-36 PH of at least 4.9 (22)	—	178	203
SF-36 MH	29/28 (22; 34)	41/42 (33; 51)*	46/50 (39; 54)*
Patients with ↑ SF-36 MH of at least 4.9 (22)	—	157	188

TABLE 2 | Quality-of-life indicators in patients from the second group (*marks statistically significant changes ($p < 0.05$) compared to pre-op values).

Parameters	Pre-op (338)	Up to 1 year (213)	Over 1 year (111)
Group 2 ODI	58/60 (52; 66)	26/24 (16; 36)*	24/22 (6; 38)*
Patients with ↓ ODI of at least 12.8 (22)	—	181	80
SF-36 PH	26/26 (22; 30)	38/38 (32; 45)*	41/43 (32; 51)*
Patients with ↑ SF-36 PH of at least 4.9 (22)	—	156	76
SF-36 MH	27/26 (20; 32)	41/38 (33; 53)*	44/49 (35; 54)*
Patients with ↑ SF-36 MH of at least 4.9 (22)	—	144	70

Patients from the third group ($n = 51$) underwent high-complexity operations using two surgical approaches, such as ALIF and LLIF with TPF, in one session. The total number of operations in this group included 51 initial operations and 6 reoperations.

Clinical Effectiveness

The mean hospital length of stay after MIS decompression alone in patients from the first group was 5.6 bed-days, intraoperative blood loss−117/50 (50; 100) ml, surgical time−84/75 (60; 100) min. **Table 1** shows the treatment results in 262 patients assessed at long-term follow-up. The complete assessment of all clinical and radiographic criteria after treatment was performed in 423 (68%) patients from the first group. Some patients were included in the assessment several times during the present study. The cumulative 5-year reoperation rate in the first group was 15.3%, and reoperation frequency−12.6%.

In the second group, the mean LOS was 8.3 days due to MIS. Surgical time of MIS TLIF direct decompressions [189/180 (150; 215)] was significantly longer compared to indirect decompressions with spinal stabilization [156/155 (130; 176)], the overall mean value being 184 min. Intraoperative blood loss was higher in TLIF operations, the overall mean value in the second group being 277/200 (100; 300) ml due to the use of MIS techniques. Assessment of all clinical criteria and quality-of-life indicators was performed in 282 patients (83%) from the second group. The assessment period was 28.9/24 (15; 41.8) months, see **Table 2**. The cumulative 5-year reoperation rate in the second group was 14.3%, and reoperation frequency 10.2%.

The mean LOS in the third group was 8.6 days due to the use of MIS techniques in all patients. Intraoperative blood loss was 260/200 (150; 275) ml. Although the surgical time for two-stage operations was 264/245 (210; 295) min, which is considered a predictor of a higher rate of severe complications (14) (surgical time > 180 min in geriatric patients), the use of MIS techniques for deformity correction made it possible to minimize the complication rate and reduce it to 31.4%. Long-term follow-up for 43 (84%) patients showed satisfactory results in most cases, see **Table 3**.

TABLE 3 | Quality-of-life indicators in the long-term follow-up for patients from the third group (*marks statistically significant changes (p < 0.05) compared to preoperative values).

Parameter	Pre-op ($n = 51$)	Long term ($n = 43$)
Group 3 ODI	56/54 (45; 62)	35/42 (22; 51)*
Patients with ↓ ODI of at least 12.8 (22)	—	38
SF-36 PH	25/24 (22; 28)	33/25 (24; 38)*
Patients with ↑ SF-36 PH of at least 4.9 (22)	—	38
SF-36 MH	26/26 (22; 28)	38/35 (28; 46)*
Patients with ↑ SF-36 MH of at least 4.9 (22)	—	37

Complication Analysis

The surgical time, unplanned readmission within 90 days after the operation, and LOS (bed-days) were taken into account separately for the patients with and without complications, and cumulative complication rates were calculated for various surgical options. All revision operations performed in the follow-up period in the patient who underwent initial operations at our medical center were taken into consideration to calculate the cumulative reoperation rate.

A total of 256 complications (25.3% from 1.013) were registered, out of which 254 (25.1% from 1.013) were recorded within 90 days after the operation, see **Table 4**.

It is worth noting a small number of complications (31.4%) after two-stage corrective lumbar spine operations for degenerative scoliosis deformities in elderly patients with concomitant obesity and comorbidity burden.

Cumulative reoperation rate for lumbar spine operations in the third group of patients could not be assessed in the five-year follow-up period due to insufficient observation time, but the cumulative reoperation rate for the three-year follow-up was 7.8%, and so was reoperation frequency.

The total number of complications in the studied patient cohort was 256 (25.3%). Complications were significantly more rare in patients from group 1 compared to groups 2 and 3 ($p <$

TABLE 4 | Complications found following the Dindo-Clavien classification criteria (2004) in the three groups of patients.

Type	Complication	Group 1	Group 2	Group 3	Total
I	Blood loss of at least 500 ml	16	50	2	68
	Dural tear (no post-op CSF leak)	47	18	—	65
	Rao grade 1–2 lateral screw malposition	—	22	—	22
	Cortical endplate injury	—	8	1	9
	Cage migration	—	2	—	2
	Bone cement leakage to the spinal canal, paravertebral vein.	—	1	1	2
	Peritoneal injury	—	1	—	1
II	Increasing neurological deficit	6	8	3	17
	Blood loss of over 500 ml with blood transfusion		8	2	10
	Hematoma (epidural, retroperitoneal)	3	2	1	6
	Exacerbation of chronic urinary tract infection	2	2	1	5
	Superficial surgical site infection (SSI)	—	5	—	5
	Residual radicular pain syndrome	3	—	—	3
	Allergic response	1	—	—	1
	Acute psychoorganic syndrome	—	1	—	1
	Decompensated cardiovascular pathology	—	1	—	1
	Acute deep lower limb venous thrombosis	—	—	1	1
IIIA	Pharmacoresistant neuropathic pain syndrome	2	3	1	6
	Dural tear with CSF leak (external lumbar drainage)	—	1	—	1
IIIB	Short-term disc reherniation (up to 90 days)	8	—	—	8
	Epidural hematoma	4	—	—	4
	Incomplete decompression	3	1	—	4
	Rao grade 3 intracanal screw malposition (reoperation)	—	2	2	4
	Deep surgical site infection	1	2	—	3
	Short-term segmental instability (up to 90 days)	3	—	—	3
	Pseudoarthrosis (reoperation)	—	1	1	2
	Fixation hardware failure (reoperation)	—	1	—	1
IVA	Acute myocardial infarction	—	1	—	1
Total		99	141	16	256
		15.9%	41.7%	31.4%	25.3%

0.001 and $p = 0.01$). All complications were divided into general, instrumentation-related, and neurological.

General Complications

Blood loss of at least 500.0 ml was the most common intraoperative complication (78 cases) amounting to 30.5% of the total number. Blood volume deficit was compensated by blood products (blood transfusion) in 10 of these cases. It is worth mentioning that in the vast majority of cases (58) this complication occurred in patients from group 2, who underwent TLIF. General complications also included intraoperative dural tears in 66 cases (25.8% of all complications), out of which in one case external CSF leak confirmed by MRI control was observed in the early postoperative period. The liquor fistula was closed in a course of conservative treatment combined with external lumbar drainage. Incidental durotomy was significantly more often observed in patients from group 1 (47 patients out of 66). Intraoperative dural suturing with adhesive sealing and local tissue grafting was performed in all patients with dural tears.

Slow (over 10 days) postoperative wound healing (superficial SSI) in patients with diabetes mellitus was observed in five cases. All wounds were healed by primary intention. Other short-term postoperative complications in the form of residual compression with clinical manifestations (4 cases) and long-term ones in the form of deep SSI (three cases), where postoperative wound revision was required, were observed only in groups 1 and 2. Residual radicular pain syndrome associated with nerve root traction injury in 3 patients from group 1 was reversed by conservative treatment. Within 90 days of the follow-up, early disc reherniation requiring hospital readmission and revision operation was observed in 8 patients from group 1 who underwent microsurgical discectomy (6 patients) and over-the-top decompression (2 patients). Clinical instability syndrome confirmed by functional radiography developed in 3 cases after spinal canal decompression for central stenosis, as a result of excessive resection of osseous and ligamentous structures. These patients received stabilization TLIF surgery.

Control MRI scans showed asymptomatic epidural hematomas in five cases fully lysed in the course of conservative treatment. They also showed retroperitoneal hematoma requiring follow-up and conservative treatment along the surgical approach in an early postoperative period after LLIF

in one patient. Epidural hematomas were accompanied by clinical signs of cauda equina root compression requiring revision operation in 4 patients from group 1. All those patients received indirect coagulants long before the operation due to a concomitant cardiovascular pathology. Decompensated cardiovascular pathology (arterial hypertension), acute myocardial infarction, and deep left lower limb venous thrombosis were recorded in one case each. Conservative treatment was performed successfully in all cases. Acute psychoorganic syndrome in the form of delirium and allergic response was recorded in one case each as well. Exacerbation of urinary tract infection in the early postoperative period was discovered in 5 patients who received antibacterial therapy based on urine culture results and antibiotic sensitivity. Intraoperative peritoneum injury during ALIF surgery was recorded in one case, but it did not affect the postoperative course. Overall, general complications were recorded in 191 cases amounting to 74.6% of the total number of complications.

Instrumentation-Related Complications

Intraoperative vertebral body endplate injury was discovered in 9 cases, of which 5 during TLIF and 4 during LLIF. In one case, this instrumentation-related complication after TLIF led to pseudoarthrosis with interbody cage migration, which required a revision operation 10 weeks after the initial operation. Bone block formation was observed in 8 other cases in the long-term follow-up.

According to the postoperative MSCT scan, Rao grade 3 intracanal transpedicular screw malposition (18) requiring reoperation was discovered in four patients, and Rao grade 1–2 lateral screw malposition with no clinical signs was observed in 22 patients after TLIF surgery. Bone cement leakage with no clinical signs was recorded in two cases, of which one was spinal canal leakage, and one was paravertebral vein leakage. According to control MSCT scans, interbody cage migration with no clinical symptoms not requiring revision operation was discovered in two patients three months after the initial operation. Control examination showed hardware failure associated with pseudoarthrosis and requiring revision operation in two patients with recurrent spinal pain syndrome 7 and 11 months after the initial operation. Overall, 42 instrumentation-related complications amounting to 16.4% of the total number of complications were recorded.

Neurological Complications

An increasing neurological deficit in lower limbs was observed in the early postoperative period in 17 patients, 8 of them from group 2. In 14 of those cases, neurological status deterioration was caused by intraoperative nerve root retraction injury, which required long-term conservative therapy. In 3 cases, the post-LLIF complication was caused by surgical nerve root injury on the approach side. In two of those cases, improvement was observed in course of conservative therapy and rehabilitation activities. One female patient exhibited neurological deficit as persistent right hip flexor weakness on the approach side. Pharmacoresistant neuropathic pain syndrome developed within a year after the initial operation in six patients.

TABLE 5 | Main characteristics of groups of patients with and without complications.

Parameter	Without complications	With complications	*p*
Number of patients	804	209	-
Age	66.2/65 (62; 69)	66.3/65 (62; 69)	0.992
Gender, % female	62%	70%	0.096
BMI	31.3/30.9 (27.6; 34.7)	32.5/31.7 (27.9; 36.9)	0.013
CCI, %	62.8/77 (53; 90)	64.2/77 (53; 90)	0.643
LOS (total within 90 days)	6.3/6 (5; 7)	9.3/7 (6; 11)	<0.0001
Primary LOS	6.3/6 (5; 7)	8.2/7 (6; 10)	<0.0001
Surgical time (total within 90 days)	113.7/90 (65; 150)	194./182,5 (125; 235)	<0.0001
Surgical time (initial)	113.7/90 (65; 150)	176.8/170 (110; 221.2)	<0.0001

TABLE 6 | BMI effect on LOS, blood loss, surgical time (rs is Spearman's correlation coefficient, and *p* is a statistical significance level).

Parameters	Group 1		Group 2		Group 3	
Value	rs	*p*	rs	*p*	rs	*p*
LOS	0.15	0.0001	0.04	0.48	0.25	0.07
Surgical time	0.26	<0.0001	0.15	0.007	−0.04	0.76
Blood loss	0.22	0.0001	0.16	0.004	0.18	0.21

All those patients responded positively to test stimulation, and chronic epidural stimulation systems were implanted. Overall, 23 neurological complications amounting to 9.0% of all complications were recorded.

It is worth noting that most complications (141) were recorded in group 2 accounting for 55.1% of all complications, which may be explained by the extent of the operations and their surgical technicalities.

Among a total of 256 complications, 254 (99%) developed within 90 days, 226 (88.3%) were identified as mild (Dindo-Clavien types I, II, and IIIA), and 30 (11.7%)—as severe (types IIIB and IVA). In 29 of the latter cases, reoperation under general anesthesia was required. The characteristics of patients with complications are presented in **Table 5**.

Statistically significant differences were observed between these two groups in BMI ($p = 0.013$), which indicates an adverse effect of obesity on the complication rate. Significant differences were also identified in surgical time (initial operations took longer in the patients who later exhibited complications, $p < 0.0001$), and LOS (the number of bed-days was higher in patients with complications, $p < 0.0001$).

The distribution of complications ($n = 256$) with respect to operation complexity was as follows: 99 (38.7%) after low-complexity operations (decompression alone), 136 (53.1%) after intermediate-complexity operations (MIS TLIF), and 21 (8.2%) after high-complexity operations (ALIF and LLIF). The number of patients without complications ($n = 804$) after low-complexity operations was 536 (85.9%), after intermediate-complexity operations-−190 (64.6 %), and after high-complexity

operations—78 (82.1%). Thus, a higher complication rate was identified in patients, who underwent intermediate-complexity operations (MIS TLIF), as opposed to low- and high-complexity surgical procedures ($p < 0.001$ and $p = 0.001$, respectively), which is probably due to higher risks of dural tears and intraoperative bleeding in direct microsurgical decompressions compared to indirect techniques.

The LOS ($n = 1\ 013$) after initial operation was 6.7/6 (5; 8) bed-days (0 to 31 days). LOS in patients without complications was 6.3/6 (5; 7) (1–19 days), and for patients with complications-−9.3/7 (6; 11) bed-days (2–31 days), the obtained differences being statistically significant ($p < 0.0001$).

Effect of Excess Body Mass on Complication and Reoperation Rates

The effect of obesity and concomitant somatic pathology on the quality of life, functional status and pain syndrome, surgical time, LOS, blood loss parameters, reoperation rate, complication rate, and nature of complications was investigated. The obtained results were analyzed in the three groups of patients.

The BMI value in group 1 was 30.6/30.1 (26.8; 33.6), in group 2 - 33.2/33 (28.8; 36.6), and in group 3−32.9/33.5 (29.2; 36.3). In group 1, it was significantly lower than that in groups 2 and 3 ($p < 0.001$ and $p = 0.002$, respectively).

Obesity (BMI $\geq$ 30) was diagnosed in 582 (57.5%) patients from the studied cohort. In group 1, BMI values of 30 and above were recorded in 50.6% (316) cases, whereas in group 2—in 68.0% (230) patients, and in group 3—in 36 patients (70.6%). Thus, excess body mass (BMI $\geq$ 30) appears to be a risk factor of segmental instability and degenerative lumbar spine deformity in elderly patients.

Correlation dependences between BMI and intraoperative blood loss, surgical time and LOS are presented in **Table 6**.

The increase in BMI correlates significantly with higher surgical time in groups 1 and 2, but this correlation does not hold for group 3 where higher surgical time is primarily explained by surgical technicalities. Similarly, higher intraoperative blood loss in groups 1 and 2 correlates with higher BMI, but the correlation does not hold for group 3 patients for the same reasons. The increase in LOS is associated with higher BMI only in group 1, but the correlation does not hold for groups 2 and 3.

Reoperation frequency dependences on BMI in different patient groups were compared. The number of patients requiring lumbar spine reoperation throughout the follow-up period and the number of patients with sufficient prospective follow-up time are shown in **Table 7**.

Analysis of the correlation between BMI and reoperation period in the studied groups showed that reoperations within 1 year after the initial operation were not associated with BMI. However, the reoperations performed 2 or 3 years after the initial operation were often in patients with increased BMI. The BMI effect of on reoperation frequency was analyzed in two periods: up to 12 months and after 12 months.

The patients were divided into two groups based on extent of operation and surgical injury and comparable BMI values as follows: local microsurgical decompressions (624 operations) and decompressive operations with spinal stabilization and corrective operations (389 operations). The data on BMI values for patients with and without reoperations are presented in **Table 8**.

TABLE 7 | Periodical reoperation frequency estimates and their dependence on BMI.

Prospective follow-up time	BMI below 30		BMI of 30 and above		Comparison (*p*)
Group 1 (*n* = 624)					
0–1 year	20 from 308	6.5%	22 from 316	7.0%	0.87
1–2 years	5 from 308	1.6%	10 from 316	3.2%	0.3
2–3 years	1 from 242	0.4%	5 from 259	1.9%	0.22
3–4 years	0 from 186	0.0%	1 from 194	0.5%	1
4–5 years	1 from 93	1.1%	3 from 106	2.80%	0.62
Total	9.6% in 5 years		15.4% in 5 years		—
Group 2 (*n* = 338)					
0–1 year	4 from 108	3.7%	7 from 230	3.0%	0.75
1–2 years	1 from 108	0.9 %	5 from 230	2.2%	0.67
2–3 years	1 from 78	1.3%	3 from 179	1.7%	1
3–4 years	0 from 58	0.0%	5 from 127	3.9%	0.33
4–5 years	0 from 33	0.0%	1 from 72	1.4%	1
Total	5.9 % in 5 years		12.2% in 5 years		—
Group 3 (*n* = 51)					
0–1 year	0 from 15	0.0%	4 from 36	10.0%	0.31
1–2 years	0 from 15	0.0%	0 from 36	0.0%	1
2–3 years	0 from 8	0.0%	0 from 21	0.0%	1
3–4 years	0 from 4	0.0%	1 from 10	10.0%	—
4–5 years	0 from 0	—	1 from 1	—	—
Total	not enough data		not enough data		—

TABLE 8 | BMI comparison for patients with and without reoperations.

Postoperative period	BMI (initial operation) for patients without reoperations in the period of interest (1)	BMI (initial operation) for patients with reoperations (2)	BMI (reoperation) for patients with reoperations (3)	Statistical significance p, comparison (1) – (3)	Statistical significance p, comparison (1) – (2)
Local microsurgical decompressions ($n = 624$)					
Up to 1 year	30.5/30.0 (26.7; 33.3)	31.1/30.4 (27.2; 34.4)	30.2/30.1 (26.6; 34)	$p = 0.86$	$p = 0.52$
After 1 year		32.6/32.9 (28.5; 35.9)	32.7/32.5 (29.4; 36.8)	$p = 0.02$	$p = 0.03$
Decompressions with spinal stabilization and corrective operations ($n = 389$)					
Up to 1 year	33.0/32.8 (28.5; 36.4)	32.7/33.8 (30.1; 35)	32.2/31.5 (27.6; 36.6)	$p = 0.72$	$p = 0.96$
After 1 year		35.6/36.2 (32.6; 38.1)	34.6/35.3 (31.4; 38.1)	$p = 0.13$	$p = 0.03$

TABLE 9 | BMI effect on quality of life (rs is Spearman's correlation, p is statistical significance level).

Parameters	Pre-op	0–1 year	1–2 years	2–3 years	3–4 years
VAS spine	0.09 ($p = 0.04$)	0.03 ($p = 0.53$)	0.25 ($p < 0{,}001$)	0.14 ($p = 0.24$)	0.28 ($p = 0.01$)
VAS leg	−0.03 ($p = 0.50$)	0.01 ($p = 0.82$)	0.30 ($p < 0.001$)	0.14 ($p = 0.24$)	0.14 ($p = 0.22$)
ODI	0.02 ($p = 0.63$)	0.09 ($p = 0.07$)	0.27 ($p < 0.001$)	0.12 ($p = 0.3$)	0.26 ($p = 0.02$)
SF-36 PH	0 ($p = 0.99$)	−0.06 ($p = 0.26$)	−0.28 ($p = 0.001$)	−0.19 ($p = 0.18$)	−0.34 ($p = 0.01$)
SF-36 MH	0 ($p = 0.95$)	−0.08 ($p = 0.14$)	−0.22 ($p = 0.01$)	−0.15 ($p = 0.3$)	−0.27 ($p = 0.06$)

Regardless of operation extent and surgical injury, BMI showed no effect on reoperation frequency within the first 12 months after the initial operation. It is primarily explained by the fact that vast majority of reoperations (73.7%) within the first follow-up year were caused by postoperative complications (residual compression, epidural hematomas, early disc reherniation, transpedicular screw malposition, cage migration, etc.). However, from the second follow-up year onward lumbar spine reoperation frequency was significantly higher in patients with obesity both after local microsurgical decompressions and decompressions with spinal stabilizations and corrective operations, statistical significance level being the same ($p = 0.03$). It is worth noting that patients after operations with hardware placement tended to lose some weight after the initial operation (lower BMI before the reoperation, $p = 0.058$), whereas patients after decompressions tended to have almost the same mean BMI before reoperation, despite weight loss recommendations given before hospital discharge.

Analysis of BMI correlation with quality of life, functional adaptation, and postoperative back and lower limb pain intensity within the first year after the initial operation showed the lack of correlation between the parameters of interest, see **Table 9**.

However, a significant adverse effect of increased BMI on lower limb and back pain indicators, functional adaptation, and quality of life is determined after 1 year from the initial operation was observed. Despite some degree of irregularity in the long term, the adverse effect of BMI on pain intensity and quality of life remained a clear trend.

Distribution of complications according to the Dindo-Clavien classification across groups of the patients with BMI values below and over 30 is presented in **Table 10**.

Comparison of complication rates in the patients with various BMI values showed higher rates for patients with obesity ($p = 0.007$).

A multifactor logistic regression model was used to identify complication predictors among the factors as follows: age, gender, BMI, and operation complexity based on surgical time and surgical injury estimates. A final regression model included only two factors: BMI and operation type (decompression alone, TLIF, ALIF/LLIF).

Quality metrics of the regression model were as follows: AUC = 0.64, sensitivity = 0.60, specificity = 0.69. The obtained Odd Ratios described the risks as follows:

- When the patient's BMI increased by 1, the complication rate was multiplied by 1.003 if operation type was the same;
- Complication rate for TLIF compared to decompression was multiplied by 1.223 (22.3% higher) if BMI value was the same;
- Complication rate for ALIF, LLIF compared to decompression was multiplied by 1.031 (3.1% higher) if BMI value is the same.

The obtained data showed the complication rate for TLIF surgery in patients with obesity increased by 22.3% compared to decompression, whereas for indirect decompression techniques, such as ALIF and LLIF, the complication rate only increased by 3.1 %.

Thus, obesity in elderly patients increases the probability of clinical instability syndrome that manifests in most cases in the form of degenerative spondylolisthesis with clinically significant spinal canal stenosis. In these cases, direct nerve root decompression, spondylolisthesis reduction, and rigid transpedicular fixation are required to eventually increase the complication rates, even when MIS techniques are used.

TABLE 10 | Complication distribution as per the Dindo-Clavien classification across groups of the patients with and without obesity.

Type	Complication	BMI < 30	BMI ≥ 30	Total
I	Blood loss of at least 500 ml	22	46	68
	Dural tear (no post-op CSF leak)	31	34	65
	Rao grade 1–2 lateral screw malposition	5	17	22
	Cortical endplate injury	4	5	9
	Cage migration	—	2	2
	Bone cement leakage to spinal canal, paravertebral vein.	—	2	2
	Peritoneal injury		1	1
II	Increasing neurological deficit	7	10	17
	Blood loss of over 500 ml with blood transfusion	2	8	10
	Hematoma (epidural, retroperitoneal)	1	5	6
	Exacerbation of chronic urinary tract infection	1	4	5
	Superficial SSI	1	4	5
	Residual radicular pain syndrome due to incomplete decompression	1	2	3
	Allergic response		1	1
	Acute psychoorganic syndrome	1		1
	Decompensated cardiovascular pathology		1	1
	Acute deep lower limb venous thrombosis		1	1
IIIA	Pharmacoresistant neuropathic pain syndrome	2	4	6
	Dural tear with CSF leak (external lumbar drainage)	—	1	1
IIIB	Short-term disc reherniation (up to 90 days)	3	5	8
	Epidural hematoma	3	1	4
	Incomplete decompression	1	3	4
	Rao grade 3 intracanal screw malposition (reoperation)	—	4	4
	Deep SSI	1	2	3
IIIB	Short-term segmental instability (up to 90 days)	2	1	3
	Pseudoarthrosis (reoperation)	1	1	2
	Fixation hardware failure (reoperation)	—	1	1
IVA	Acute myocardial infarction	1	—	1
Total		90	166	256
		20.9%	28.5%	25.3%

Comorbidity Index Effect of on Complication and Reoperation Rates

The effect of the Charlson Comorbidity Index (CCI) on surgical treatment results in elderly patients with degenerative lumbar spine pathology was investigated. Somatic comorbidity was discovered in 999 (98.6%) patients, of which 155 (15.3%) had an isolated pathology, while the vast majority of patients (844 (83.3%) had a concomitant pathology.

The mean CCI value in group 1 was 64%, in group 2—62%, and in group 3—58% with no statistically significant differences between them. It was found that the presence of a concomitant somatic pathology and a patient's age significantly increased postoperative LOS in group 1, while no such effect is observed in groups 2 and 3 (see **Table 11**).

Correlation analysis of the effect the CCI had on the pain syndrome intensity, functional adaptation, and quality of life in the patients with concomitant pathology at different follow-up times was performed (see **Table 12**).

Table 12 demonstrates that at the preoperative stage the CCI significantly correlates with all the parameters of interest, except for the leg pains primarily associated with nerve root compression in the spinal canal. This correlation indicates the significant effect of somatic comorbidity on quality of life in elderly patients with degenerative lumbar spine pathologies. In addition, the CCI correlated with spinal pain intensity from the third follow-up year onward, as opposed to lower limb pain, which was only associated with the severity of concomitant pathology in the first year after the operation. The statistically significant effect of concomitant pathologies on the physical health indicators (SF-36 PH) and quality of life observed in the first year after the operation was seemingly associated with persistent surgical site pain, motion restrictions, and additional difficulties of the rehabilitation stage in the elderly and geriatric patients with severe somatic pathologies. The severity of the concomitant pathology had no significant effect on the parameters of interest in the second follow-up year due to stabilization of a patient's general condition and lumbar spine condition in particular (which is to be considered as a favorable outcome of surgical treatment). However, the effect of the CCI on the quality of life increased around the fourth follow-up year,

TABLE 11 | CCI effect on postoperative LOS, blood loss, surgical time (rs is Spearman's correlation coefficient, *p* is statistical significance level).

Parameters	Group 1		Group 2		Group 3	
Value	**Rs**	***p***	**rs**	***P***	**rs**	***p***
LOS	−0.15	0.0006	−0.07	0.22	−0.13	0.35
Surgical time	−0.07	0.11	0.02	0.8	−0.01	0.92
Blood loss	−0.03	0.56	0.04	0.46	0.21	0.14

TABLE 12 | CCI effect on the quality of life (rs is Spearman's correlation coefficient, *p* is statistical significance level).

Parameters	Pre-op	0–1 year	1–2 years	2–3 years	3–4 years
VAS spine	−0.10 ($p = 0.03$)	−0.07 ($p = 0.19$)	−0.10 ($p = 0.19$)	−0.28 ($p = 0.01$)	−0.31 ($p = 0.006$)
VAS leg	−0.07 ($p = 0.13$)	−0.15 ($p = 0.004$)	0.06 ($p = 0,45$)	−0.06 ($p = 0.62$)	−0.21 ($p = 0.07$)
ODI	−0.16 ($p < 0.001$)	−0.13 ($p = 0.01$)	−0.01 (=0,9)	−0.12 ($p = 0.31$)	−0.34 ($p = 0.002$)
SF-36 PH	0.12 ($p = 0.01$)	0.12 ($p = 0.04$)	0.03 ($p = 0.74$)	−0.13 ($p = 0.4$)	0.19 ($p = 0.2$)
SF-36 MH	0.14 ($p = 0.003$)	0,08 ($p = 0.15$)	0.02 ($p = 0.79$)	0.03 ($p = 0.85$)	0.21 ($p = 0.16$)

which was seemingly associated with the progression of both spinal degenerative changes, including degenerative changes in major lower limb joints, and somatic comorbidity in elderly patients due to aging. All these factors caused loss of functional adaptation and quality-of-life deterioration.

The effect of osteoporosis on the quality of life and surgical treatment results was studied in 389 patients who received decompressions with spinal stabilization and corrective operations. Osteoporosis with a T-score below −2.5 was observed in 35 patients (9% of the studied sample), of whom 31 (89%) were females. In all these cases, TPF was combined with polymethylmethacrylate augmentation of the lumbar vertebral bodies via fenestrated screws to increase the resistance of hardware elements to pull-out force. Correlation analysis did not show that osteoporosis had any significant effect on the quality of life in elderly and geriatric patients in the long-term follow-up. However, we identified a significant effect ($p = 0.045$) of the T- score characterizing bone mineral density on the occurrence rates of instrumentation-related complications, such as transpedicular screw malposition, cage migration, and vertebral endplate injuries (see **Figure 1**).

The T-score values in patients with instrumentation-related complications ($n = 38$) were −1.41/−1.5 (−1.8; −1.1) compared to −0.92/−0.45 (−1.8; 0.0) in patients without said complications ($n = 351$). A statistically significant effect ($p = 0.045$) of T score values characterizing bone mineral density on instrumentation-related complication rate was found. TPF in elderly and geriatric patients was combined with vertebral body augmentation in 9% of cases.

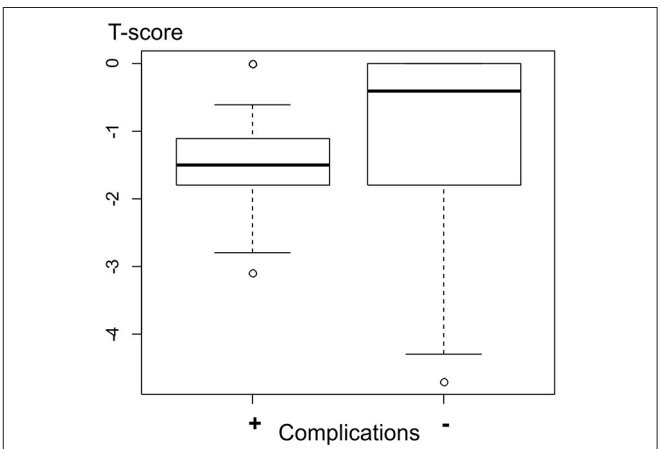

FIGURE 1 | T-score values in patients with complications were −1.41/−1.5 (−1.8; −1.1), and in patients without complications were −0.92/−0.45 (−1.8; 0.0).

DISCUSSION

To identify complication predictors as factors of unfavorable outcomes in elderly patients receiving surgical treatment for degenerative lumbar spine pathology, the Dindo-Clavien criteria as a validated and unified assessment tool were applied. Such parameters as the age, gender, BMI, and operation type were analyzed.

To identify complication predictors as factors of unfavorable outcomes in elderly patients receiving surgical treatment for degenerative lumbar spine pathology, the Dindo-Clavien criteria as a validated and unified assessment tool were applied. Such parameters as the age, gender, BMI, and operation type were analyzed.

Any complication per the Dindo-Clavien classification increased the mean LOS regardless of the operation type. Type II and IIIB complications contributed most to increased LOS. Type IIIB complications requiring hospital readmission and reoperation significantly increased the mean LOS and most often developed after TLIF. Meanwhile, type II complications contributed most to increased LOS after indirect

decompressions with spinal stabilization and corrective ALIF and LLIF operations.

Our data showed that instrumentation-related complications, such as deep SSI, clinical segmental instability, hardware failure, and Rao grade 3 transpedicular screw malposition, appear to be the most significant complications contributing to increased LOS and, as a result, higher inpatient treatment costs and quality-of-life deterioration in the first 90 days after the initial operation. It is worth noting that decompensated cardiovascular pathology in the early postoperative period significantly increased LOS, which is crucial for elderly patients with comorbidity burden.

A total of 13 patients were readmitted to our center due to complications in 90 days after their initial operations, and 13 more patients underwent redoes within their primary hospital stay. The mean period from the initial operation to hospital readmission was 35 days. The unplanned readmission rate due to complications discovered in the first 90 days in the studied cohort was 1.3%. That can be explained by the use of minimally invasive techniques, which is also confirmed by several authors (33).

The mean LOS was 6.7 days due to the use of MIS techniques in all cases. As a result, we were able to return patients to activity earlier and intensify rehabilitation procedures, thereby reducing the occurrence rate of severe complications in the early postoperative period. The mean intraoperative blood loss was reduced to 178 ml due to available MIS options. Surgical time of over 180 min is considered an important predictor of severe postoperative complications in the lumbar spine in elderly patients (14). The mean surgical time in the studied cohort, including corrective operations for degenerative deformities, was 127 min, which made it possible to minimize the number of complications.

Overall, the occurrence rate of intra- and postoperative complications as per the Dindo-Clavien classification in elderly and geriatric patients with degenerative lumbar spine pathology at 90-day follow-up was 25.1%, which agrees with published literature data (14, 21, 24).

The vast majority of complications in the studied cohort were mild complications (type I, II, and IIIA) accounting for 88.3% of all cases, intraoperative blood loss and dural tear being the most common. The occurrence of complications significantly increased LOS in this category of patients from 6.3/6 (5; 7) (without complications) to 9.3/7 (6; 11) (with complications) ($p < 0.0001$). Increased LOS due to complications is confirmed by the literature data as well (21).

Among several factors affecting complication frequency, the complexity of the surgical procedure was a statistically significant one. Simpler operations have milder complications and lower complication rates (34). MIS TLIF had the highest number of complications compared to decompressions and operations from anterior and lateral approaches since it is the complexity and operation type that determine the surgical time and intraoperative blood loss.

Our data demonstrated the unplanned readmission rate of 1.3% at 90-day follow-up, which is significantly lower than the literature data. The cumulative reoperation rate at 5-year follow-up was 15.2%, and reoperation frequency−12.1%. The analysis of surgical treatment results in 2 320 elderly patients by Saleh et al. showed a readmission rate of 6.39% and complication rate of 16.34%, including fatal outcomes (0.43%) (14). The authors concluded that increased operative times and instrumentation and fusion procedures were strongly associated with an increased risk of developing a complication. However, the authors only analyzed geriatric patients (>80 years) at 30-day follow-up. In addition, the study took into consideration various types of lumbar spine surgical procedures, including primarily open operations, in particular with elongated multilevel fixation hardware. The authors did not use the Dindo-Clavien classification in their complication analysis.

In a multicenter prospective cohort study searched for perioperative complications of spine surgery in 270 patients >80 years of age (35). Overall perioperative complications were observed in 20%, surgical site complications were observed in 8.1%, and minor systemic complications were observed in 14.8% of patients. The reoperation rate was 4.1%. Decreased daily activity, instrumentation surgery, and an operative time >180 min were found to be associated with minor systemic complications. Long fixations resulted in increased morbidity but not mortality.

In Camino Willhuber et al. (21), the reoperation frequency was 11.72%, and the complication rate as per the Dindo-Clavien classification−28.83%. The authors only analyzed elderly patients (with a mean age of 68 years) at 90-day follow-up. Various types of surgical procedures involving all spinal regions were taken into consideration, including primarily open operations not involving MIS techniques. BMI, surgical time, intraoperative blood loss, and operation complexity were identified as complication risk factors in both papers.

Thus, obesity turns out to be among the main predictors of unfavorable surgical outcomes in elderly and geriatric patients with degenerative lumbar spine pathology, even when minimally invasive surgical options are available (36). Increased BMI leads to higher surgical time, which in turn leads to higher intraoperative blood loss and a higher complication rate. The adverse effect of obesity on the occurrence rate of continued degenerative changes in operated segments and adjacent-level pathologies, especially after decompressions with spinal stabilization is not to be overlooked as well. Eventually, this scenario increases the number of unfavorable outcomes and quality-of-life deterioration in both short- and long-term follow-up.

The CCI also has an adverse effect on the quality-of-life indicators, since a high comorbidity burden combined with excess body mass significantly reduces the potential for returning patients to activity in the early postoperative period and favors decompensated cardiovascular pathology and exacerbation of other chronic diseases.

In all elderly patients, avoiding complications related to comorbidities should be the main concern before planning surgery (37). After evaluation of deconditioning, sarcopenia, malnutrition, dementia, and polypharmacy, all measures are implemented in a 6-week presurgical period, including prerehabilitation, nutritional supplementation, medication changes, and preoperative medication for postoperative pain control to minimize delirium. Enhanced recovery after

surgery protocols have been shown to be effective at reducing perioperative morbidity and costs, while improving outcomes.

According to meta-analysis some authors recommend that all patients who are >75 years of age be referred to the geriatric medicine clinic for a frailty assessment, because frailty is an important predictor of postoperative complications, increased hospital stays, and mortality (38).

Studying complications in patients of the older age group, we can be concluded that preparation for a planned surgical intervention should begin in advance. It is necessary to take into account all the nuances, including the rejection of certain drugs and diet (39). Despite the fact that some complications, especially those related to the surgical technique, depend only on the experience and actions of the surgeon during the operation, there are a sufficient number of modifiable predictors that can be corrected (40). Understanding this situation allows surgeons to minimize the unfavorable prognosis using an integrated approach to the planned treatment.

Operation complexity also factors in an increased number of unfavorable surgical outcomes in elderly patients with obesity and comorbidity burden, which agrees with the literature data (34). It is worth noting that the occurrence rate of adjacent level pathology increases significantly after rigid segmental fixation, especially in the case of multilevel lesions (36). The more complex and time-consuming an operation is, the higher the complication rate. Therefore, surgical treatment for degenerative lumbar spine pathology in this age group should be decided based on the minimization of surgical aggression (41). Comparable clinical effectiveness is ensured by isolating the prevalent clinical syndrome and selecting a surgical option, including MIS techniques, to reverse the main clinical manifestations of the disease accompanying degenerative pathology.

With the development of advanced image guidance systems, the popularity of minimally invasive procedures has increased. Serious efforts are under way to shorten the learning curve, reduce specific complications make indications more specific, and minimize heterogeneous clinical outcomes. However, minimally invasive techniques in the treatment of LSS are still under development and many guidelines and high-quality studies have been published about the safety and efficacy of these techniques in the past decade (42).

Dagistan et al. examined the effect of minimally invasive decompression surgery on quality of life in 37 elderly patients (between 65 and 86 years old) with spinal stenosis (43). They concluded that decompressive surgeries without instrumentation in elderly patients increased quality of life significantly. The rate of complications was very low. In cases in which complications developed, they could be managed easily. Considering this the surgical intervention itself must be performed using MIS technology, choosing the most effective volume and access in this particular case, which reduces the risk of complications (44, 45).

To improve the outcomes of spine surgery in geriatric patients, Zileli and Dursun also recommend implementation of the following measures: meticulous evaluation of comorbidities, preoperative treatment for some diseases, strict measures to treat osteoporosis, good surgical planning, and use of minimally invasive surgeries as much as possible (38).

This research, however, is subject to several limitations: its retrospective nature, and the limitation to a single center. Also, some patients were lost to the long-term follow-up for various reasons that is a certain limitation which did not allow us to calculate the full percentage of complications on the entire set of patients.

CONCLUSIONS

A registry of postoperative complications is an important tool for health quality assessment and choosing a surgical option that helps to establish measures to reduce such complications. A complication rate depends on several factors such as obesity, comorbidity burden, and operation complexity being the most statistically significant. Using MIS techniques for treating elderly patients reduces the number of severe complications.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of FSBI Federal Neurosurgical Center Novosibirsk, Russia. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

VK, AE, and EA contributed to conception and design of the study and organized the database. EA performed the statistical analysis. AE wrote the first draft of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

REFERENCES

1. Fehlings MG, Tetreault L, Nater A, Choma T, Harrop J, Mroz T, et al. The aging of the global population: the changing epidemiology of disease and spinal disorders. *Neurosurgery*. (2015) 77 (Suppl. 4):S1–5. doi: 10.1227/NEU.0000000000000953
2. Peake CM. Low back pain in adults. *InnovAiT*. (2019) 12:643–9. doi: 10.1177/1755738019869374
3. Jakola AS, Sørlie A, Gulati S, Nygaard OP, Lydersen S, Solberg T. Clinical outcomes and safety assessment in elderly patients undergoing decompressive laminectomy for lumbar spinal stenosis: a prospective study. *BMC Surg.* (2010) 10:34. doi: 10.1186/1471-2482-10-34
4. Deyo RA, Hickam D, Duckart JP, Piedra M. Complications after surgery for lumbar stenosis in a veteran population. *Spine*. (2013) 38:1695–702. doi: 10.1097/BRS.0b013e31829f65c1

5. Morgalla MH, Noak N, Merkle M, Tatagiba MS. Lumbar spinal stenosis in elderly patients: is a unilateral microsurgical approach sufficient for decompression? *J Neurosurg Spine.* (2011) 14:305–12. doi: 10.3171/2010.10.SPINE09708
6. Arinzon Z, Adunsky A, Fidelman Z, Gepstein R. Outcomes of decompression surgery for lumbar spinal stenosis in elderly diabetic patients. *Eur Spine J.* (2004) 13:32–7. doi: 10.1007/s00586-003-0643-7
7. Cassinelli EH, Eubanks J, Vogt M, Furey C, Yoo J, Bohlman HH. Risk factors for the development of perioperative complications in elderly patients undergoing lumbar decompression and arthrodesis for spinal stenosis: an analysis of 166 patients. *Spine.* (2007) 32:230–5. doi: 10.1097/01.brs.0000251918.19508.b3
8. McClendon J Jr, Smith TR, Thompson SE, Sugrue PA, O'shaughnessy BA, Ondra SL, et al. The impact of body mass index on hospital stay and complications after spinal fusion. *Neurosurgery.* (2014) 74:42–50; discussion 50. doi: 10.1227/NEU.0000000000000195
9. Chapin L, Ward K, Ryken T. Preoperative depression, smoking, and employment status are significant factors in patient satisfaction after lumbar spine surgery. *Clin Spine Surg.* (2017) 30:E725–32. doi: 10.1097/BSD.0000000000000331
10. Elsayed G, Davis MC, Dupépé EC, McClugage SG, Szerlip P, Walters BC, et al. Obese (body mass index >30) patients have greater functional improvement and reach equivalent outcomes at 12 months following decompression surgery for symptomatic lumbar stenosis. *World Neurosurg.* (2017) 105:884–94. doi: 10.1016/j.wneu.2017.06.072
11. Castle-Kirszbaum MD, Tee JW, Chan P, Hunn MK. Obesity in neurosurgery: a narrative review of the literature. *World Neurosurg.* (2017) 106:790–805. doi: 10.1016/j.wneu.2017.06.049
12. Aalto TJ, Malmivaara A, Kovacs F, Herno A, Alen M, Salmi L, et al. Preoperative predictors for postoperative clinical outcome in lumbar spinal stenosis: systematic review. *Spine.* (2006) 31:E648–63. doi: 10.1097/01.brs.0000231727.88477.da
13. Mannion AF, Fekete TF, Porchet F, Haschtmann D, Jeszenszky D, Kleinstück FS. The influence of comorbidity on the risks and benefits of spine surgery for degenerative lumbar disorders. *Eur Spine J.* (2014) 23 (Suppl. 1):S66–71. doi: 10.1007/s00586-014-3189-y
14. Saleh A, Thirukumaran C, Mesfin A, Molinari RW. Complications and readmission after lumbar spine surgery in elderly patients: an analysis of 2,320 patients. *Spine J.* (2017) 17:1106–12. doi: 10.1016/j.spinee.2017.03.019
15. Manson N, Hubbe U, Pereira P, Lam K, Fuster S. Senker W. Are the outcomes of minimally invasive transforaminal/posterior lumbar fusion influenced by the patient's age or BMI? *Clin Spine Surg.* (2020) 33:284–91. doi: 10.1097/BSD.0000000000001019
16. Meyerding HW. Spondylolisthesis; surgical fusion of lumbosacral portion of spinal column and interarticular facets; use of autogenous bone grafts for relief of disabling backache. *J Int Coll Surg.* (1956) 26:566–91.
17. White AA, Panjabi MM. *Clinical Biomechanics of the Spine*. Philadelphia: JB Lippincott (1990).
18. Rao G, Brodke DS, Rondina M, Bacchus K, Dailey AT. Inter- and intraobserver reliability of computed tomography in assessment of thoracic pedicle screw placement. *Spine.* (2003) 28:2527–30. doi: 10.1097/01.BRS.0000092341.56793.F1
19. Charlson ME, Pompei P, Ales KL, MacKenzie CR. A new method of classifying prognostic comorbidity in longitudinal studies: development and validation. *J Chronic Dis.* (1987) 40:373–83. doi: 10.1016/0021-9681(87)90171-8
20. de Groot V, Beckerman H, Lankhorst GJ, Bouter LM. How to measure comorbidity. A critical review of available methods. *J Clin Epidemiol.* (2003) 56:221–9. doi: 10.1016/S0895-4356(02)00585-1
21. Camino Willhuber G, Elizondo C, Slullitel P. Analysis of postoperative complications in spinal surgery, hospital length of stay, and unplanned readmission: application of dindo-clavien classification to spine surgery. *Global Spine J.* (2019) 9:279–86. doi: 10.1177/2192568218792053
22. Copay AG, Glassman SD, Subach BR, Berven S, Schuler TC, Carreon LY. Minimum clinically important difference in lumbar spine surgery patients: a choice of methods using the oswestry disability index, medical outcomes study questionnaire short form 36, and pain scales. *Spine J.* (2008) 8:968–74. doi: 10.1016/j.spinee.2007.11.006
23. Dindo D, Clavien PA. What is a surgical complication? *World J Surg.* (2008) 32:939–41. doi: 10.1007/s00268-008-9584-y
24. Bellut D, Burkhardt JK, Schultze D, Ginsberg HJ, Regli L, Sarnthein J. Validating a therapy-oriented complication grading system in lumbar spine surgery: a prospective population-based study. *Sci Rep.* (2017) 7:11752. doi: 10.1038/s41598-017-12038-7
25. Tan GH, Goss BG, Thorpe PJ, Williams RP. CT-based classification of long spinal allograft fusion. *Eur Spine J.* (2007) 16:1875–81. doi: 10.1007/s00586-007-0376-0
26. Greiner-Perth R, Boehm H, Allam Y, Elsaghir H, Franke J. Reoperation rate after instrumented posterior lumbar interbody fusion: a report on 1680 cases. *Spine.* (2004) 29:2516–20. doi: 10.1097/01.brs.0000144833.63581.c1
27. Kreiner DS, Shaffer WO, Baisden JL, et al. An evidence-based clinical guideline for the diagnosis and treatment of degenerative lumbar spinal stenosis (update). *Spine J.* (2013) 13:734–43. doi: 10.1016/j.spinee.2012.11.059
28. Sengupta DK, Herkowitz HN. Lumbar spinal stenosis. Treatment strategies and indications for surgery. *Orthop Clin North Am.* (2003) 34:281–9511. doi: 10.1016/S0030-5898(02)00069-X
29. Palmer S, Turner R, Palmer R. Bilateral decompressive surgery in lumbar spinal stenosis associated with spondylolisthesis: unilateral approach and use of a microscope and tubular retractor system. *Neurosurg Focus.* (2002) 13:E4. doi: 10.3171/foc.2002.13.1.5
30. Akram D S. Obesity: Preventing and managing the global epidemic. *World Heal Organ Tech Rep Ser.* (2000) 894:I–XII+1–253.
31. *R Core Team R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing: Vienna, Austria (2020). Available online at: http://www.r-project.org/index.html (accessed April 09, 2022).
32. Agha RA, Sohrabi C, Mathew G, Franchi T, Kerwan A, O'Neill N; PROCESS Group. The PROCESS 2020 guideline: updating consensus preferred reporting of CasESeries in surgery (PROCESS) guidelines. *Int J Surg.* (2020) 84:231–5.
33. Byvaltsev VA, Kalinin AA, Stepanov IA, Aliyev MA, Shepelev VV. Pestryakov YuYa. Meta-analysis of prospective cohort studies that compare outcomes of minimally invasive and open transforaminal lumbar interbody fusion in surgical treatment of patients with lumbar spine degenerative disease. *Orthopaedic Genius.* (2019) 25:111–9. doi: 10.18019/1028-4427-2019-25-1-111-119
34. Byvaltsev VA, Kalinin AA, Egorov AV, Okoneshnikova AK. Comparative analysis of the clinical efficacy of minimally invasive surgical techniques in the treatment of patients with a disco-radicular conflict of the lumbar spine. *Endoscopic surgery.* (2019) 25:35–42. doi: 10.17116/endoskop20192501135
35. Watanabe T, Kanayama M, Takahata M, Oda I, Suda K, Abe Y, et al. Perioperative complications of spine surgery in patients 80 years of age or older: a multicenter prospective cohort study. *J Neurosurg Spine.* (2019) 17:1–9. doi: 10.3171/2019.9.SPINE19754
36. Klimov VS, Evsyukov AV, Kphalepa RV, Ryabykh SO, Amelina EV, Markin SP, et al. Analysis of the structure of revision interventions in elderly and senile patients with degenerative pathology of the lumbar spine. *Neurosurgery.* (2021) 23:47–61. doi: 10.17650/1683-3295-2021-23-1-47-61
37. Chakravarthy VB, Yokoi H, Coughlin DJ, Manlapaz MR, Krishnaney AA. Development and implementation of a comprehensive spine surgery enhanced recovery after surgery protocol: the Cleveland Clinic experience. *Neurosurg Focus.* (2019) 46:E11. doi: 10.3171/2019.1.FOCUS18696
38. Zileli M, Dursun E. How to improve outcomes of spine surgery in geriatric patients. *World Neurosurg.* (2020) 140:519–26. doi: 10.1016/j.wneu.2020.04.060
39. Mikhail C, Pennington Z, Arnold PM, Brodke DS, Chapman JR, Chutkan N, et al. Minimizing blood loss in spine surgery. *Global Spine J.* (2020) 10(Suppl. 1):71S—83S. doi: 10.1177/2192568219868475
40. Ton A, Shahrestani S, Chen XT, Ballatori AM, Wang JC, Buser Z. The effect of modifiable risk factors on postoperative complications in lumbar spine fusions. *Global Spine J.* (2021) 21925682211022315. doi: 10.1177/21925682211022315
41. Klimov VS, Vasilenko II, Evsyukov AV, Khalepa RV, Amelina EV, Ryabykh SO, et al. Use of LLIF technology in adult patients with degenerative scoliosis: retrospective cohort analysis and literature review. *Orthopaedic*

Genius. (2018) 24:393–403. doi: 10.18019/1028-4427-2018-24-3-393-403
42. Kiliçaslan ÖF, Nabi V, Yardibi F, Tokgöz MA, Köse Ö. Research tendency in lumbar spinal stenosis over the past decade: a bibliometric analysis. *World Neurosurg*. (2021) 149:e71–84. doi: 10.1016/j.wneu.2021.02.086
43. Dagistan Y, Dagistan E, Gezici AR, Cancan SE, Bilgi M, Cakir U. Effects of minimally invasive decompression surgery on quality of life in older patients with spinal stenosis. *Clin Neurol Neurosurg*. (2015) 139:86–90. doi: 10.1016/j.clineuro.2015.09.009
44. Chi KY, Cheng SH, Kuo YK, Lin EY, Kang YN. Safety of lumbar interbody fusion procedures for degenerative disc disease: a systematic review with network meta-analysis of prospective studies. *Global Spine J*. (2021) 11:751–60. doi: 10.1177/2192568220938024
45. Zhu L, Wang JW, Zhang L, Feng XM. Outcomes of oblique lateral interbody fusion for adult spinal deformity: a systematic review and meta-analysis. *Global Spine J*. (2022) 12:142–54. doi: 10.1177/2192568220979145

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CASE REPORT
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Percutaneous Transforaminal Full-Endoscopic Removal of Neurinoma of the Fifth Lumbar Nerve Root With Intraoperative Neuromonitoring: A Case Report

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Background: Technical achievements and surgical techniques improvement contribute to the expansion of the endoscopic spine surgery possibilities. However, today there are few reports about the use of percutaneous endoscopy in spinal tumor surgery. A case of percutaneous transforaminal endoscopic removal of the lumbar spinal nerve tumor with intraoperative neuromonitoring is presented.

Case Description: A 59-year-old female was complaining of a left shin and foot pain, weakness, and paresthesia. Preoperative magnetic resonance imaging (MRI) revealed a tumor (neurinoma) at the left L5-S1 intervertebral foramen. Transforaminal endoscopic removal of an extramedullary tumor from an 8-mm skin incision with intraoperative neuromonitoring was performed. Postoperative MRI revealed the signs of total resection of the tumor.

Conclusion: The presented case confirms that percutaneous endoscopic removal of lumbar spine intraforaminal neurinomas can be safe and effective.

Keywords: percutaneous endoscopic surgery, full-endoscopic spine surgery, transforaminal approach, spinal oncology, intraforaminal neurinoma

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INTRODUCTION

Percutaneous full-endoscopic spine surgery is known for over 30 years (1). However, only in the 2000s, it became popular in clinical practice thanks to development of the surgery technique of a percutaneous endoscopic access to the spinal canal and clear visualization of neural structures (2–4). During that period, the approach changed from spinal arthroscopy (discoscopy) to spinal neuroendoscopy. It triggered a fast improvement of the technique itself and upgrade of surgical instruments for percutaneous endoscopy of the spine, thereby determining new indications for this type of surgery. Meeting all criteria for minimally invasive surgery, percutaneous endoscopic interventions are of great interest to specialists and in demand by patients (5).

Main indication for percutaneous endoscopic intervention on the spine is degenerative–dystrophic pathologies (6). Apart from that, this technique has been tried in infectious spine diseases (7, 8); chronic epidural hematoma (9); and spine stabilization and its complications (10–12).

In 2012, first reports were published on percutaneous endoscopy for extradural neoplasms of the spine (13, 14), and in 2019 for removal of intradural extramedullary tumors (15). However, the surgical technique, safety, and efficiency of percutaneous endoscopy for spine tumors have not been sufficiently described in the publications. This paper presents a case report of full-endoscopic transforaminal removal of lumbar neurinoma with intraoperative neurophysiological monitoring.

Clinical Case

A 59-year-old woman admitted to our clinic, with constant left leg pain lasting for 2 years. Over the past 6 months, there was a gradual increase in pain intensity up to 7–8 Visual analogue scale (VAS) scores. Magnetic resonance imaging (MRI) showed a tumor of the left L5 spinal nerve at the level of the intervertebral foramen (**Figures 1A–C**).

Neurological status: moderate paresis of the left foot extensors (3 points), Lasègue's sign on the left, throbbing pain and paresthesia in the L5 dermatome on the left, and no negative sensitive signs.

Electroneuromyography (ENMG) showed decreased amplitudes of motor responses on the left in abduction of *m. extensor digitorum brevis* by 30% compared to the right side. As to *mm. peroneus longus*, *tibialis anterior* on the left, no spontaneous activity was detected, motor unit potentials were not changed, and the interference pattern was complete. The ENMG data match a mild axonal preganglionic lesion at the L5 level on the left.

We decided to perform percutaneous full-endoscopic resection of the L5 spinal nerve tumor using a left-sided foraminal approach.

Anesthesia and Neurophysiological Monitoring

The patient received total intravenous anesthesia with propofol and fentanyl. Muscle relaxants were used only for tracheal intubation.

Intraoperative neurophysiologic monitoring included spontaneous electromyography (free-run EMG) and monopolar direct nerves stimulation (NIM 3.0, Medtronic, Minneapolis, MN, USA). Motor-evoked potentials were recorded with needle electrodes within target muscles located by the anatomical myotomes [*mm. extensor digitorum brevis* (L5), *tibialis anterior* (L5), and *gastrocnemius* (S1) on the left]. Filter setting was made as follows: low-pass filter 30 Hz and high-pass filter 3,000 Hz. We used monopolar continuous cathode rhythmic stimulation with rectangular 4-Hz impulses, stimulus time 0.1 ms, and stimulus intensity ranging from 1.0 to 2.0 mA. Cathode monopolar stimulation was made with a modified elongated probe (based on Medtronic probe, USA) through the working channel of the endoscope. A standard needle electrode was placed at the edge of the surgical wound as reference. Monopolar stimulation was made during surgical intervention in order to assess the L5 nerve and its conductivity. Direct nerve stimulation during tumor removal at intensity 1.0 mA evoked motor potentials of the target myotome muscles of the L5 motor root. During the tumor removal no parameters of the recorded motor response significantly varied. Spontaneous electromyography at the tumor removal stage recorded patterns of minimal mechanical impact like single-spike waves in *mm. tibialis anterior*, *extensor digitorum brevis*.

SURGERY

On 27 October 2021, surgery was performed with the patient in the prone position. Guided by fluoroscopy, a puncture needle 18G was placed to the intervertebral joint L5-S1 through a point located 10 cm to the left of the midline. A guide pin was inserted along the needle, and the needle was removed. A linear cut 8-mm long was made. A soft tissue retractor was introduced into the wound along the guide pin. A working tube with diameter 7 mm was placed along the retractor, after which the pin and the retractor were removed (**Figures 2A,B**).

TESSYS, Joimax® (Germany) endoscope was inserted into the working tube. Further manipulations were controlled by video endoscopy under continuous irrigation with normal saline

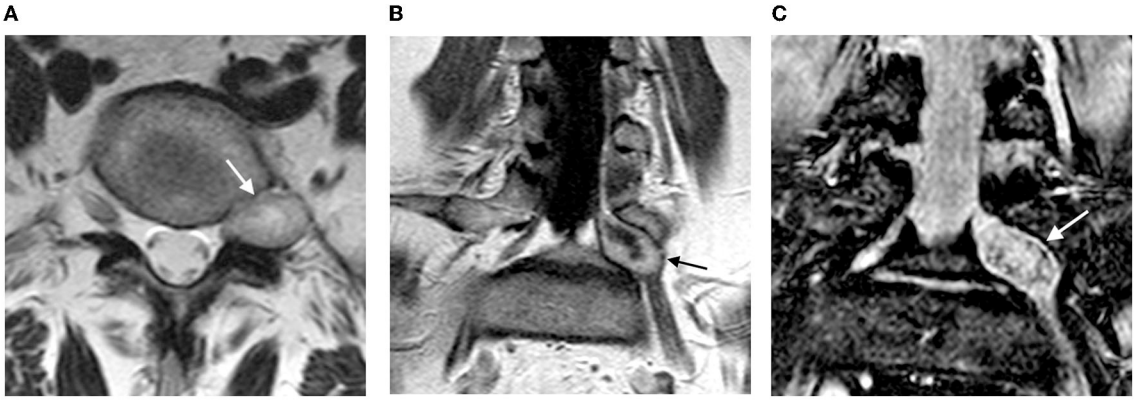

FIGURE 1 | Magnetic resonance imaging of the lumbar spine: **(A)** axial view, T2-WI mode; **(B)** frontal view, T1-WI contrast mode; **(C)** frontal view, T1-FS post-contrast (arrow shows a cystic-solid tumor of the spinal nerve, size 3.2 × 1.5 × 1.5 cm; the tumor accumulates contrast).

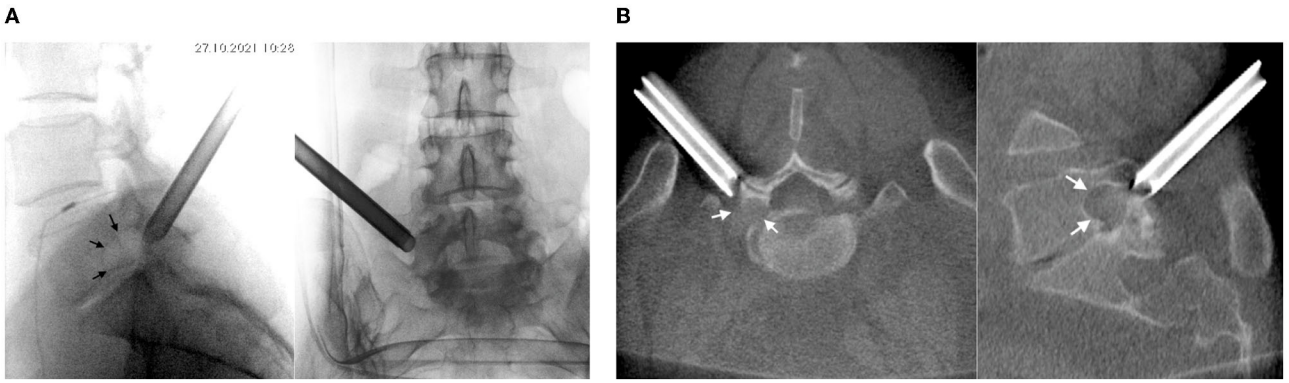

FIGURE 2 | Intraoperative **(A)** X-rays and **(B)** CT (O-arm) of the position of the working tube at the left intervertebral foramen L5-S1 (see arrows).

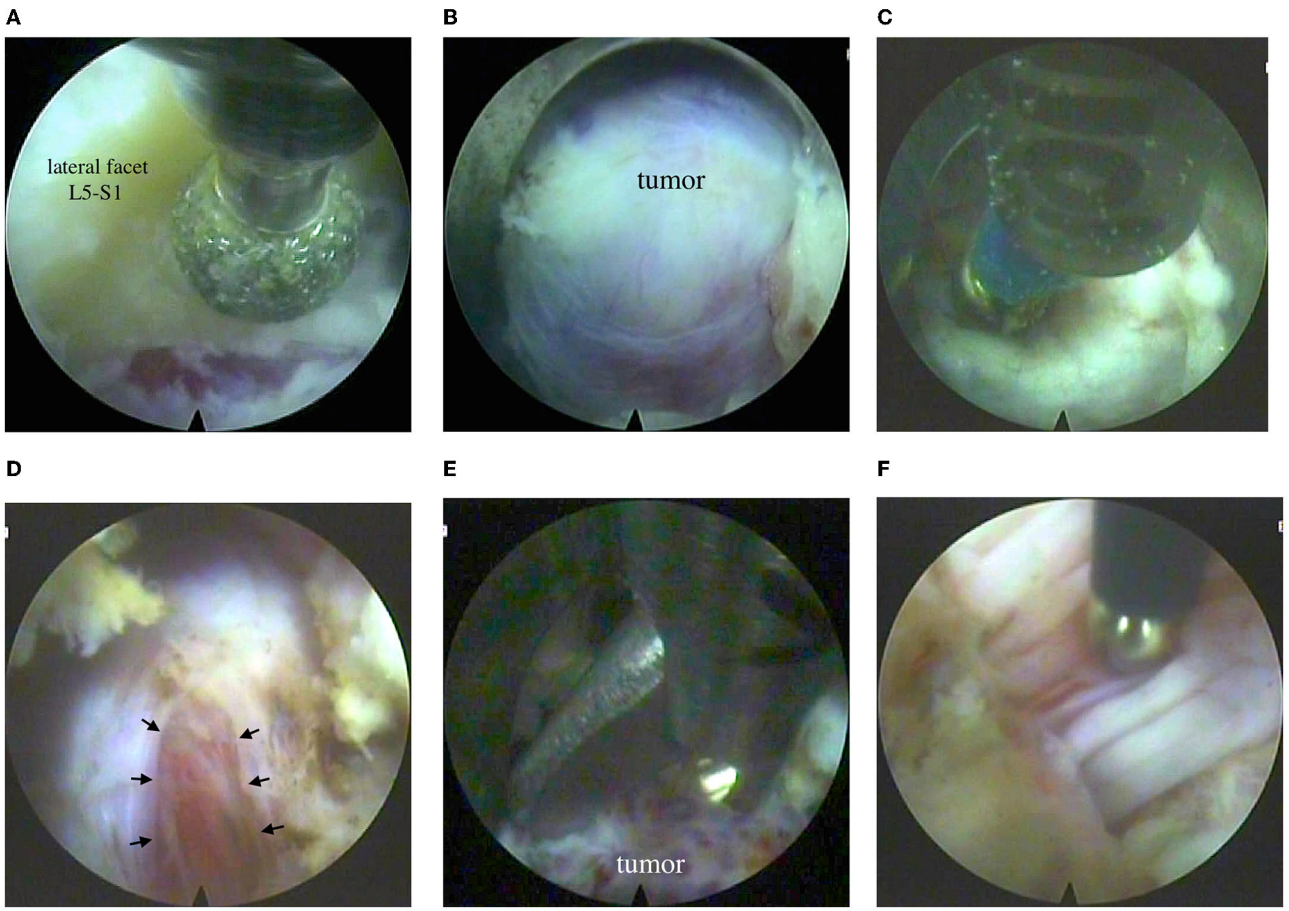

FIGURE 3 | Endoscopic step of the surgery: **(A)** partial resection of the L5-S1 lateral facet on the left with a burr; **(B)** view of the tumor in the intervertebral foramen; **(C)** bipolar electrocoagulation of the nerve sheath; **(D)** incision of the nerve sheath (see arrow); **(E)** removal of the tumor with forceps; **(F)** monopolar stimulation of the nerve bundles with a modified elongated probe (based on Medtronic probe, USA).

solution. The intervertebral joint L5-S1 was visualized. A partial lateral facetectomy was performed with a high-speed burr (**Figure 3A**). An expansive growth of the tumor resulted in enlarged intervertebral foramen, so there was no need in foraminoplasty. An intraforaminal tumor located inside the L5 spinal nerve was seen (**Figure 3B**).

After electrocoagulation on a small portion of the nerve sheath, an incision was made to see moderately vascularized

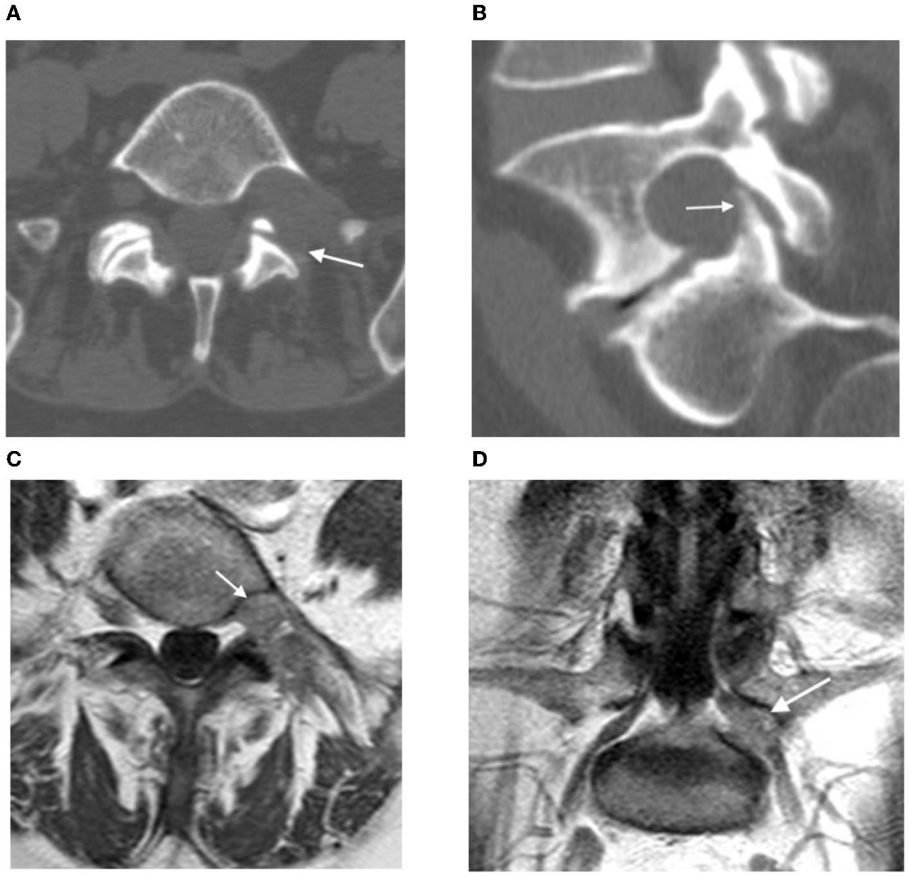

FIGURE 4 | (A,B) Postoperative CT: the arrow shows the resection area of the left intervertebral joint L5-S1; **(C,D)** contrast-enhanced MRI 3 months after surgery: postoperative changes in the left L5 root (see arrow), no signs of contrast accumulation.

tissue of the tumor, grayish-red in color, of soft consistency (**Figures 3C,D**). The tumor was removed, and functions of active motor nerve bundles were intact, which was confirmed by neuromonitoring (**Figures 3E,F**). Bleeding from the tumor vessel was controlled by bipolar coagulation. After a temporary stop of irrigation, endoscopic signs of stable hemostasis and the absence of the leakage of cerebrospinal fluid were revealed. The skin wound was sutured with 1 knotted suture. Blood loss was <30 ml; the surgery lasted for 120 min.

Result of Pathological Test: Neurinoma (Grade I)

Upon discharge, the patient had a regress in severe pain of the left leg and Lasègue's sign. Postoperative CT confirmed bone resection in the extent of partial lateral facetectomy (**Figures 4A,B**).

The control contrast-enhanced MRI on the next day and 3 months after the surgery verified total tumor resection, with no accumulation of contrast agent (**Figures 4C,D**).

After 4-month follow-up, paresis of the big toe extensor on the left foot remained, up to 3 scores. Occasionally, the patient feels a slight throbbing pain in the L5 dermatome on the left (2 VAS scores).

DISCUSSION

The report above describes one of lumbosacral neurinoma surgical treatment methods. By Kato classifications (1993), the lesion corresponds to intraforaminal neurinoma type II (16).

There are few reports on neurinoma removal by full endoscopy. Wang et al. presented a successful percutaneous foraminal endoscopic removal of *dumbbell-shaped* neurinomas, up to 4 cm in size, in 12 patients (17). The authors suggested the following advantages of this surgery method:

1. The trajectory of transforaminal endoscopic access is optimal for localization of neurinoma.
2. Minimally invasive approach does not require significant bone resection or lead to iatrogenic spinal instability.
3. Modern advancements in transforaminal percutaneous endoscopy allow total removal of the tumor not only

between the vertebral foramen, but in the spinal canal and extraforaminal area during one surgery.

We fully agree with Wang et al. in terms of the advantages of percutaneous endoscopic resection of intraforaminal neurinomas. However, we do not share their opinion that intraoperative neurophysiological monitoring is inexpedient. The authors back up their position by very rare neurological disorders after total resection of the neurinoma and consider it appropriate to transect the affected nerve completely (17).

Researchers have proved that the risk of developing a neurological deficit after removal of neurinomas and neurofibromas with complete transection of the supporting nerve can reach 23% (18), while plegia is registered in 3% of cases (19). Such conditions are caused by the rare variants of growth of motor root neurinoma (19), and by incomplete compensatory innervation of the muscles by adjacent spinal nerves roots (20). Therefore, in order to assess the risks and clarify the surgical tactics for spinal neurinomas, it is necessary to use electrophysiological control at pre- and intraoperative stages (19). In our opinion, this rule should also be applied to percutaneous endoscopic surgery.

In the case presented herein, preoperative ENMG confirmed a partially impaired conduction along the L5 root, which corresponded to the severity of neurological disorders. Intraoperative neuromonitoring with NIM3.0 system (Medtronic, USA) during percutaneous videoendoscopic resection of L5 neurinoma ensured the safety of surgical procedures, made it possible to remove tumors completely and partially retain anatomical integrity of the affected nerve, which made a positive effect on the functional outcome of treatment.

There are no previous reports on application of neurophysiological monitoring with direct monopolar nerve stimulation in percutaneous neuroendoscopic interventions on the spine (17, 21). Perhaps, it results from the lack of electrodes with the size sufficient for introducing them through the endoscope work channel. We modified a cathode monopolar stimulation probe (Medtronic, USA) by increasing its length.

Obvious obstacles to a widespread use of uniportal percutaneous endoscopic surgery for spine and spinal cord tumors today can be formulated as follows (11, 15, 17, 22, 23):

1. limited nature of methods of hemostasis and visualization of sources of bleeding;
2. lack of effective methods for sealing of the dura mater during removal of intradural neoplasms;
3. *coaxial method* of visualization and manipulation;
4. long time required for a specialist to learn the surgery technique.

Intense bleeding greatly worsens the video endoscopic image of the surgery cavity and increases the risk of complications (22). Currently known ways of hemostasis during percutaneous endoscopic removal of the spine neoplasms and spinal cord (preoperative embolization, coagulation, increased irrigation pressure, blood pressure control, etc.) are not enough (23, 24). On top of that, increased irrigation pressure after opening of the dura mater can cause complications due to intracranial hypertension (15). Therefore, percutaneous endoscopic removal of a well-vascularized tumor must be made by an experienced surgeon, otherwise preference must be given to an open intervention (24). The same principle must be applied to tumors of large size and high density (11). In our case, intraoperative bleeding was moderate, so we could use standard methods for endoscopic hemostasis.

There are different methods of sealing the dura mater in percutaneous endoscopic interventions. Conservative tactics for small defects in the dura mater, combined with hypotensive syndrome therapy, appear to be most effective (25–27). Among surgical methods to close defects in the dura mater, the most optimized are conversion to microsurgery (25), suture of the dura mater through an endoscope by Youn's technique (28), and sealing with tissue adhesive (15). In our case, extra-arachnoid localization of neurinoma did not require the dura mater plastics.

The above-listed challenges of the surgery methods can be overcome by using percutaneous unilateral biportal endoscopic technique, which has been widely developing in recent years (29). In particular, a clipping method can be good for large defects in the dura mater (27). Apart from that, percutaneous biportal endoscopy allows abandoning coaxial imaging and switching to a bimanual surgical technique, more familiar to the surgeon (30).

CONCLUSION

The presented case herein shows that uniportal full-endoscopic resection of intraforaminal neurinomas of the lumbar spine with intraoperative neurophysiological monitoring is safe and effective. Further study of potential benefits and effectiveness of percutaneous endoscopic removal of spine and spinal cord tumors must involve a larger number of cases within comparative study.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MK, SM, OM, and DA contributed to the conception and design of the study, the analysis and interpretation of data, and the

work draft. MK and SM designed figures and video. VM and DS offered guidance in study design and revised the article critically for important intellectual content. All authors read and approved the final version of the manuscript.

REFERENCES

1. Schreiber A, Suezawa Y. Transdiscoscopic percutaneous nucleotomy in disk herniation. *Orthop Rev*. (1986) 15:35–8.
2. Yeung AT, Tsou PM. Posterolateral endoscopic excision for lumbar disc herniation: surgical technique, outcome, and complications in 307 consecutive cases. *Spine.* (2002) 27:722–31. doi: 10.1097/00007632-200204010-00009
3. Schubert M, Hoogland T. Endoscopic transforaminal nucleotomy with foraminoplasty for lumbar disk herniation. *Oper Orthop Traumatol.* (2005) 17:641–61. doi: 10.1007/s00064-005-1156-9
4. Ruetten S. The full-endoscopic interlaminar approach for lumbar disc herniations. In: *Minimally Invasive Spine Surgery*. Berlin; Heidelberg: Springer. (2021). p. 346–55.
5. Chung AS, McKnight B, Wang JC. Scientific view on endoscopic spine surgery: can spinal endoscopy become a mainstream surgical tool? *World Neurosurg.* (2021) 145:708–11. doi: 10.1016/j.wneu.2020.05.238
6. Hofstetter CP, Ahn Y, Choi G, Gibson JNA, Ruetten S, Zhou Y, et al. AOSpine consensus paper on nomenclature for Working-Channel endoscopic spinal procedures. *Global Spine J.* (2020) 10:111S−21S. doi: 10.1177/2192568219887364
7. Ito M, Abumi K, Kotani Y, Kadoya K, Minami A. Clinical outcome of posterolateral endoscopic surgery for pyogenic spondylodiscitis: results of 15 patients with serious comorbid conditions. *Spine.* (2007) 32:200–6. doi: 10.1097/01.brs.0000251645.58076.96
8. Yu CH. Full-endoscopic debridement and drainage treating spine infection and psoas muscle abscess. *J Spine Surg.* (2020) 6:415–23. doi: 10.21037/jss.2020.01.04
9. Cheng YP, Lee KW, Lin PY, Huang APH, Cheng CY, Ma HI, et al. Full-endoscopic interlaminar removal of chronic lumbar epidural hematoma after spinal manipulation. *Surg Neurol Int.* (2014) 5:55. doi: 10.4103/2152-7806.131106
10. Wagner R, Iprenburg M, Telfeian AE. Transforaminal endoscopic decompression of a postoperative dislocated bone fragment after a 2-level lumbar total disc replacement: case report. *Neurosurg Focus.* (2016) 40:E8. doi: 10.3171/2015.11.FOCUS15492
11. Telfeian AE, Jasper GP, Francisco GM. Transforaminal endoscopic treatment of lumbar radiculopathy after instrumented lumbar spine fusion. *Pain Physician*. (2015) 18:179–84. doi: 10.36076/ppj/2015.18.179
12. Silva AC, de Alcantara T, Nogueira MP. The percutaneous endoscopic lumbar interbody fusion (PELIF): an advanced and innovation technique. *Int J Recent Surg Med Sci.* (2019) 5:031–4. doi: 10.1055/s-0039-1692730
13. Joo YC, Ok WK, Baik SH, Kim HJ, Kwon OS, Kim KH. Removal of a vertebral metastatic tumor compressing the spinal nerve roots via a single-port, transforaminal, endoscopic approach under monitored anesthesia care. *Pain Physician.* (2012) 15:297–302. doi: 10.36076/ppj.2012/15/297
14. Telfeian AE, Choi DB, Aghion DM. Transforaminal endoscopic surgery under local analgesia for ventral epidural thoracic spinal tumor: case report. *Clin Neurol Neurosurg.* (2015) 134:1–3. doi: 10.1016/j.clineuro.2015.03.022
15. Sentürk S., Ünsal ÜÜ. Percutaneous full-endoscopic removal of lumbar intradural extramedullary tumor via translaminar approach. *World Neurosurg.* (2019) 125:146–9. doi: 10.1016/j.wneu.2019.01.206
16. Kato T, George B, Mourier KL. Lot G, Gelbert F, Mikol J. Intraforaminal neurinoma in the lumbosacral region. *Neurol Med Chir.* (1993) 33:86–91. doi: 10.2176/nmc.33.86
17. Wang R, Chen CM, Li F, Jiang YW, Chen Y, Zheng SX. et al. Percutaneous full-endoscopic removal of lumbar dumbbell tumors viatransforaminal approach. *Zhonghua Yi Xue Za Zhi.* (2020) 100:286–90. doi: 10.3760/cma.j.issn.0376-2491.2020.04.009
18. Kim P, Ebersold MJ, Onofrio BM, Quast LM. Surgery of spinal nerve schwannoma: risk of neurological deficit after resection of involved root. *J Neurosurg.* (1989) 71:810–4. doi: 10.3171/jns.1989.71.6.0810
19. Lenzi J, Anichini G, Landi A, Piciocchi A, Passacantilli E, Pedace F, et al. Spinal nerves schwannomas: experience on 367 cases—historic overview on how clinical, radiological, and surgical practices have changed over a course of 60 years. *Neurol Res Int*. (2017) 2017:3568359. doi: 10.1155/2017/3568359
20. Hasegawa M, Fujisawa H, Hayashi Y, Tachibana O, Kida S, Yamashita J. Surgical pathology of spinal schwannoma: has the nerve of its origin been preserved or already degenerated during tumor growth? *Clin Neuropathol.* (2005) 24:19–25.
21. Kitahama Y, Matsui G, Minami M, Kawaoka T, Otome K, Nakamura M. Posterolateral percutaneous endoscopic discectomy with free-running electromyography monitoring under general anesthesia. *Mini-invasive Surg.* (2017) 1:109–14. doi: 10.20517/2574-1225.2017.11
22. Ying GY, Yao Y, Shen F, Ren YC, Chen CM, Zhu YJ. Percutaneous endoscopic removal of a lumbar epidural angiolipoma via interlaminar approach: a technical report. *World Neurosurg.* (2017) 99:59–62. doi: 10.1016/j.wneu.2016.11.088
23. Sentürk S, Ünsal ÜÜ. Percutaneous endoscopic interlaminar decompression of hypervascular spinal metastases. *World Neurosurg.* (2020) 134:182–6. doi: 10.1016/j.wneu.2019.10.175
24. Xie T, Xiu P, Song Y, Zeng J, Huang S. Percutaneous endoscopic excision and ablation of osteoid osteoma of the lumbar spine and sacrum: a technical note and outcomes. *World Neurosurg.* (2020) 133:121–6. doi: 10.1016/j.wneu.2019.09.039
25. Sencer A, Yorukoglu AG. Akcakaya MO, Aras Y, Aydoseli A, Boyali O. Fully endoscopic interlaminar and transforaminal lumbar discectomy: short-term clinical results of 163 surgically treated patients. *World Neurosurg.* (2014) 82:884–90. doi: 10.1016/j.wneu.2014.05.032
26. Soliman HM. Irrigation endoscopic decompressive laminotomy. A new endoscopic approach for spinal stenosis decompression. *Spine J.* (2015) 15:2282–9. doi: 10.1016/j.spinee.2015.07.009
27. Park HJ, Kim SK, Lee SC, Kim W, Han S, Kang SS. Dural tears in percutaneous biportal endoscopic spine surgery: anatomical location and management. *World Neurosurg.* (2020) 136:?578–?85. doi: 10.1016/j.wneu.2020.01.080
28. Shin JK, Youn MS, Seong YJ, Goh TS, Lee JS. Iatrogenic dural tear in endoscopic lumbar spinal surgery: full endoscopic dural suture repair (Youn's technique). *Eur Spine J.* (2018) 27:544–8. doi: 10.1007/s00586-018-5637-6
29. Kim JE, Yoo HS, Choi DJ, Park EJ, Jee SM. Comparison of minimal invasive versus biportal endoscopic transforaminal lumbar interbody fusion for single-level lumbar disease. *Clin Spine Surg.* (2020) 34:E64–E71. doi: 10.1097/BSD.0000000000001024
30. Heo DH, Son SK, Eum JH, Park CK. Fully endoscopic lumbar interbody fusion using a percutaneous unilateral biportal endoscopic technique: technical note and preliminary clinical results. *Neurosurg Focus.* (2017) 43:E8. doi: 10.3171/2017.5.FOCUS17146

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Prediction of Post-operative Long-Term Outcome of the Motor Function by Multimodal Intraoperative Neuromonitoring With Transcranial Motor-Evoked Potential and Spinal Cord-Evoked Potential After Microsurgical Resection for Spinal Cord Tumors

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Objective: To examine the effect of multimodal intraoperative neuromonitoring on the long-term outcome of motor function after microsurgical resection for spinal cord tumors.

Materials and Methods: Consecutive fourteen patients with spinal tumors who were surgically treated at the University of Fukui Hospital between 2009 and 2020 [M:F = 10:4, ages ranging from 22 to 83 years (mean ± SD = 58 ± 21 years)] were included in this study. There were eight intra-axial tumors and six extra-axial tumors. There were four patients with hypertension, two patients with diabetes mellitus, and four patients with hyperlipidemia. Three patients were under antithrombotic medication, two were under steroid medication, four were current smokers, and four were current drinkers. Manual muscle test (MMT) of the upper and lower extremities of the patients was examined before surgery, 2 weeks after surgery, and at the final follow-up. The mean follow-up period was 38 ± 37 months. McCormick scores were examined before surgery and at the final follow-up. Microsurgical resection of the tumor was underwent through the posterior approach under transcranial motor-evoked potential (TcMEP) monitoring. The MEP of 46 extremities was recorded during the surgery. Gross total resection was achieved in 13 of 14 surgeries. Spinal cord-evoked potential (Sp-SCEP) monitoring was performed in eight of 14 patients.

Results: The length of peritumoral edema was significantly longer in patients with deterioration of McCormick scores than in patients with preservation of McCormick scores ($p = 0.0274$). Sp-SCEP could not predict the deterioration. The ratio of MEP at the beginning of the surgery to that at the end of the surgery was the only significant negative factor that predicts deterioration of motor function of the extremity at the final

follow-up ($p = 0.0374$, odds ratio [OR] 1.02E-05, 95% CI 9.13E+01–7.15E+18). A receiver operating characteristic (ROC) analysis revealed that the cutoff value of the ratio of MEP to predict the deterioration at the final follow-up was 0.23 (specificity 100%, specificity 88%, positive predictive value 100%, and negative predictive value 88%) to predict deterioration at the final follow-up.

Conclusions: Ratio MEP was the most significant negative factor to predict the deterioration of motor weakness at spinal tumor surgery. The setting of the cutoff value should be more strict as compared to the brain surgery and might be different depending on the institutions.

Keywords: spinal tumor, motor-evoked potential, motor function, extremity, long-term outcome, McCormick score

INTRODUCTION

Surgery of spinal tumors, especially the intramedullary spinal cord tumor (IMSCT), has potential risk of sensory-motor dysfunction after surgery. Although Elsberg reported the first case of total resection of IMSCT in 1916 (1), most cases were still treated by radiation therapy after biopsy because of the high morbidity and mortality rates (2). Technical innovation, such as microscope and bipolar coagulator, has reduced the morbidity and mortality of total resection of SCT (3). Intraoperative neuromonitoring (IONM) by sensory-evoked potential (SEP) was first indicated in scoliosis surgery, which also had the risk of postoperative motor dysfunction (4). SEP could detect relatively severe injury, such as transverse spinal cord injury, but could not detect partial injury, such as anterior spinal artery syndrome (5) or motor dysfunction after surgery, for intramedullary tumor (6).

Intraoperative neuromonitoring with motor-evoked potential (MEP) by transcranial stimulation (TcMEP) in spinal surgery was first indicated in surgery of cervical spine (7, 8) and surgery of spinal cord injury (9). Afterward, MEP was applied to spinal tumor surgery (10, 11). Surgery of IMSCT under MEP was significantly related to the good outcomes of adult patients (10) and disappearance of MEP was significantly related to the deterioration of motor function immediately after surgery and at the final follow-up (11). MEP also could significantly increase the gross total resection rate (12). In surgery for 500 IMSCTs, complete resection could be achieved in 77.2% of defined endophytic tumors and 41.7% of diffuse tumors by the implementation of IONM with MEP (13). Preoperative motor dysfunction and intraoperative worsening of MEP were significantly related to the surgical outcomes (14).

The sensitivity and specificity of MEP in spinal surgery were 83 and 86%, respectively, while those of brain surgery were 100 and 62% (15, 16). Analysis of the motor function of 150 muscles in surgery of 250 IMSCTs under TcMEP provided a 5.9% of the false-positive rate, 7% of false-negative rate, and 27% of record failure rate, while TcMEP was successfully recorded in 96% of 216 aneurysm surgeries (17). TcMEP seemed more unstable or less available in spinal surgery than in brain surgery.

D-wave, directly recorded MEP from the epidural electrode after transcranial stimulation, had also developed and used in combined with TcMEP. A recent report showed that TcMEP had the highest sensitivity and D-wave had the highest specificity among TcMEP, SEP, and D-wave 19 months after surgery of 28 IMSCTs (18).

Although MEP or D-wave was proved to be the most significant predictive factor of postoperative motor dysfunction (18), the cutoff value for the prediction of postoperative motor dysfunction remains unclear. Fifty percent reduction of MEP has been used as the warning value in aneurysm surgery (10, 15), the value seemed not enough for accurate prediction in surgery for a spinal tumor. Some investigators reported more strict cutoff values, such as 70 or 80%, that might be necessary to have MEP monitoring reliable in spinal surgery (12, 16, 17). In this study, we examined the effect of multimodal mIONM with TcMEP and spinal cord-evoked potential (Sp-SCEP) on the long-term outcomes of motor function after microsurgical resection for spinal cord tumors (SCTs) with logistic regression analysis of the factors that affect surgical outcomes and with receiver operating characteristic (ROC) analysis of the cutoff value of MEP for the prediction of postoperative motor dysfunction.

MATERIALS AND METHODS

Patients

Consecutive fourteen patients with spinal who were surgically treated at the University of Fukui Hospital between 2009 and 2020 were enrolled in this retrospective study. There were ten men and four women, with ages ranging from 22 to 83 years (mean = 58 ±_21 years). There were eight intra-axial tumors and six extra-axial tumors. The mean length of the lesion and mean length that of peritumoral edema were 2.5 ±_1.2 vertebral bodies and 1.6 ±_1.8 vertebral bodies, respectively. As for underlying diseases, there were four patients with hypertension, two patients with diabetes mellitus, and four patients with hyperlipidemia. Three patients were under antithrombotic medication, two were under steroid medication, four were current smokers, and four were current drinkers. Manual muscle test (MMT) of the upper and lower extremities of the patients was examined before

Abbreviations: IONM, Intraoperative neuromonitoring; IMSCT, Intramedullary spinal cord tumor; EMSCT, Extramedullary spinal cord tumor; MEP, Motor-evoked potential; SEP, Sensory-evoked potential; mIONM, Multimodal intraoperative monitoring; SCEP, Spinal cord evoked potential; TcMEP, Motor-evoked potential by transcranial stimulation.

TABLE 1 | Summary of clinical data for the 14 patients receiving spinal tumor surgery.

Case	Age	Sex	Lesion	Site	Intraaxial or extraaxial	Length of lesion (vertebra)	Length of edema (vertebra)	Preopeartive Tc-MEP McCormick scores		Worst ratio of MEP	Sp-SCEP	Ratio of Sp-SCEP	Gross total removal	Follw up period (months)	Postopeartive McCormick scores
1	68	M	Ependymoma	C4-6	Intraaxial	2	5	3	+	0.45	–		+	1	4
2	36	M	Tumor with neurenteric cyst	C2	Intraaxial	3	1	3	+	0.08	+	0.33	–	68	3
3	36	M	Hemangioblastoma	T5-7	Extraaxial	4	4	1	+	0.59	+	1.0	+	17	1
4	79	F	Meningioma	T3-5	Extraaxial	1	0	3	+	0.6	–		+	18	1
5	45	M	Schwannnoma	C2	Extraaxial	1	0	2	+	1.0	–		+	30	1
6	62	F	Meningioma	T10	Extraaxial	1	0	1	+	0.3	+	0.8	+	50	1
7	75	M	Meningioma	T3-5	Extradural	2	0	4	+	1.29	+	0.6	+	3	4
8	31	M	Ependymoma	Th10-11	Intraaxial	2	1	2	+	0	+	1.0	+	72	3
9	72	M	Myxopapillary ependymoma	cauda equina	Intraaxial	1	1	2	+	0.09	–		+	59	3
10	28	F	Ependymoma	C4-T6	Intraaxial	13	2	4	+	0.23	+	1.0	+	1	4
11	65	M	Meningioma	C7-T1	Extraaxial	1	4	1	+	0.91	+	1.0	+	99	3
13	22	M	Schwannoma	C3	Extraaxial	1	0	1	+	0.56	–		+	2	1
12	83	M	Schwannoma	T5-7	Extraaxial	1	1	1	+	0	+	0.6	+	106	1
14	77	M	Ependymoma	L1	Intraaxial	1	4	2	+	0.77	–		+	1	3

surgery, 2 weeks after surgery, and at the final follow-up. McCormick scores of the patients were examined before surgery and at final follow-up. IONM with MEP underwent in all cases and the ratio of the amplitude of MEP at the end of surgery to that at the beginning of surgery in each extremity was calculated as Ratio MEP. Among them, the most decreased ratio in each patient was described as the worst ratio of MEP. IONM with Sp-SCEP was carried out in 8 patients. The ratio of amplitude at the end of surgery to that at the beginning of surgery was described as the ratio of Sp-SCEP. Gross total resection was achieved in 13 patients. Follow-up period was ranged from 1 to 106 months (mean ± SD = 38 ± 37 months; **Table 1**).

Surgical Resection

All patients received microsurgical resection of the tumor through a posterior approach under tcMEP monitoring. Corkscrew-shaped stimulatory electrodes of tcMEP (Unique Medical, Tokyo, Japan) were placed at the points of 1 cm posterior, 5 cm lateral to Cz. Train of five electrical stimulation with 120 mA, 500 Hz, 0.2 ms was performed. Electromyography of the thenar muscle of upper extremities and abductor pollicis muscle of lower extremities was recorded. The ratio of the amplitude of electromyography of each muscle at the end of the surgery to that at the beginning of the surgery was defined as the change of MEP. Total MEPs of 46 extremities were recorded during the surgery. The ratio of MEP at the beginning of the surgery to that at the end of the surgery was defined as Ratio MEP. Gross total resection was achieved in 13 of 14 surgeries. For Sp-SCEP, a bipolar catheter electrode was inserted into the epidural space at the rostral and the caudal side of laminectomy. Direct medullary electrical stimulations (duration: 0.1 ms, frequency 5 Hz, intensity: 1.5 mA) were performed by the bipolar electrode at the caudal side. SEP was detected by the electrode at the rostral side (high pass filter: 3,000 Hz, low pass filter: 10 Hz, 100 averaging; **Table 1**).

Statistical Analysis

Univariate analysis was performed with Pearson's chi-squared test or Fisher's exact test for categorical variables or with the Mann-Whitney U-test for numeric variables. Forward and backward stepwise logistic regression analyses with the Akaike Information Criterion (AIC) to determine the associations of potential confounders for deterioration of motor weakness at MMT at the final follow-up with the Ratio MEP, presence of preoperative motor weakness, age and sex of the patient, length of the lesion, length of peritumoral edema, history of hypertension, diabetes mellitus, hyperlipidemia, presence of antithrombotic medication, steroid medication, smoking, and drinking. ROC analysis was performed to analyze the relationship between Ratio MEP and the deterioration of MMT of 46 extremities 2 weeks after surgery and at final follow-up.

All statistical analyses were performed using JMP 15.2.0 (SAS Institute, Cary, NC, USA) and R (R Foundation for Statistical Computing, Vienna, Austria), with an error probability of <0.05.

TABLE 2 | Univariate analysis of factors associated with the deterioration of McCormick score at the final follow-up.

	Postoperative deterioration of McCormick score	Postoperative preservation or improvement of McCormick score	*p* value
Number of patients	4 (28.6%)	10 (71.4%)	
Age (years old)	60.3 ± 20.2	56.5 ± 7.0	0.7773
Female	0 (0%)	4 (40%)	0.2507
Intraaxial tumor	3 (75%)	5 (50%)	0.5804
Length of lesion	0.82 ± 0.41	1.25 ± 0.40	0.2896
Length of edema	1.73 ± 0.87	1.29 ± 0.41	0.0274*
Gloss total resection	4 (100%)	8 (80%)	1.0000
Hypertension	0 (0%)	4 (0%)	0.2507
Diabetes mellitus	1 (25%)	1 (10%)	0.5055
Hyperlipidemia	0 (0%)	4 (40%)	0.2507
Antithrombic medication	1 (25%)	2 (20%)	1.0000
Steroid medication	0 (0%)	2 (20%)	1.0000
Smoking	1 (25%)	3 (30%)	1.0000
Drinking	2 (20%)	2 (20%)	0.5205

**Means "the difference is statistically significant".*

RESULTS

Univariate Analysis of Factors Affecting the Deterioration of McCormick Scores at the Final Follow-Up

Postoperative deterioration of McCormick scores was observed in 5 patients (**Table 1**). There were 7 patients with a worst MEP ratio of less than 0.5 and 5 patients with worst MEP ratio of less than 0.3. However, the MEP ratio was not related to the postoperative deterioration of McCormick score. There was no difference in the age, sex, the number of patients with intra-axial tumor, gloss total resection, length of the lesion, the number of patients with hypertension, diabetes mellitus, antithrombotic medication, steroid medication, current smoking, and drinking between the patients with deterioration of McCormick scores and the patients with preservation of McCormick scores. Only the length of peritumoral edema was significantly longer in the patients with deterioration of McCormick scores than in the patients with preservation of McCormick scores ($p = 0.0274$; **Table 2**).

Of the 8 patients with surgery under Sp-SCEP monitoring, the ratio of Sp-SCEP was 0.33 in one patient, 0.6 in two patients, and 0.8 in one patient. However, there was no one with deterioration of McCormick scores in those patients. Among the remaining 4 patients without the reduction of Sp-SCEP, there were two (50%) patients with deterioration of McCormick scores.

Logistic Regression Analysis of Factors Affecting the Deterioration of MMT of 46 Extremities at the Final Follow-Up

Forward and backward stepwise logistic regression analyses with AIC using 13 variates revealed that the prediction model that consisted of six factors of drinking, hyperlipidemia, hypertension, presence of preoperative motor weakness, Ratio MEP, and smoking gave the minimal AIC scores (21.4). Among those factors, Ratio MEP was the only significant negative factor that predicted deterioration of motor weakness at the final follow-up ($p = 0.0374$, odds ratio [OR] 1.02E-05, 95% CI 9.13E+01–7.15E+18; **Table 3**).

ROC Analysis Between the Change of MEP and the Deterioration of MMT of 46 Extremities 2 Weeks After Surgery and Final Follow-Up

Receiver operating characteristic analysis revealed that Ratio MEP was significantly related to the deterioration of the motor function of extremities 2 weeks after surgery ($p = 0.0173$, **Figure 1A**). The cutoff value of the Ratio MEP to predict motor function of extremities 2 weeks after surgery was 0.17 (specificity 55%, specificity 99.7%, positive predictive value 60%, and negative predictive value 97%). ROC analysis also revealed that Ratio MEP was significantly related to the deterioration of the motor function at the final follow-up ($p = 0.0001$, **Figure 1B**). The cutoff value of Ratio MEP to predict the motor function of extremities at the final follow-up was 0.23 (sensitivity 100%, specificity 88%, positive predictive value 100%, and negative predictive value 88%).

Representative Cases

Case 1

A 68-year-old man with ependymoma had been suffering from progressive paresthesia, fine movement disorder, reduction of grasping power of bilateral upper extremities, and gait disturbance for 2 months. Preoperative gadolinium (Gd)-enhanced T1-weighed image (T1WI) of magnetic resonance imaging (MRI) (**Figures 2A,C**) demonstrated intra-axial tumor of the cervical spine between C4 and C6. Preoperative T2-weighted image (T2WI) of MRI illustrated edema around the tumor ranging from C2 level and C6 level (**Figure 2B**). Gross total resection of the tumor was achieved through midline myelotomy by posterior approach (**Figure 2D**). The change in the amplitude of MEP of both upper and lower extremities (UE: upper extremity, LE: lower extremity) had ranged from 91 to 108% (**Figure 2E**). Postoperative Gd-enhanced T1WI of MRI (**Figures 2F,G**) showed gross total resection of the tumor.

Case 2

A 36-year-old man with a tumor with a neurenteric cyst had been suffering from right occipital pain for 6 months. Preoperative T1WI of magnetic MRI (**Figures 3A–C**) demonstrated an intra-axial tumor of the cervical spine at C2 without edema around the tumor. Gross total resection of the tumor was achieved by a posterior approach (**Figure 3D**). However, during dissection of the tumor, the amplitude of MEP of the right upper and right lower extremities suddenly reached down to 0 and 30% as compared to the initial value, respectively (**Figure 4A**). Postoperative T1WI of MRI (**Figure 4B**) showed gross total resection of tumor. Postoperative diffusion-weighted image (DWI) of MRI (**Figure 4C**) indicated the occurrence of acute ischemic stroke of the right cervical spinal cord. Postoperative fluid-attenuated inversion recovery image (FLAIR) of MRI (**Figure 4D**) also showed the occurrence of stroke. The patient exhibited right hemiparesis, right hypesthesia of deep sensation, left hypesthesia of superficial sensation, increased deep tendon reflex, and right ankle clonus (Brown-Sequard syndrome) after surgery.

DISCUSSION

Since IONM with TcMEP was more unstable or less available in spinal surgery than in brain surgery, multimodal IONM (mIONM) was introduced. mIONM with TcMEP and SEP was first applied to spinal surgery (19–21). The sensitivity and specificity of the mIONM in surgery for spinal deformity or EMSCT or EDSCT were relatively high (20) and were significantly related to the good McCormick scores at the final follow-up in surgery of IMSCT (22). However, the sensitivity and specificity regarding the deterioration of McCormick scores were 73 and 78%, which were still low (23). In surgery for 127 cauda equina tumors, the sensitivity of root injury by triggered electromyogram (tEMG) monitoring was also 37.5%. IONM with tEMG, TcMEP, and SEP might improve the accuracy of the prediction (24).

Sensory-evoked potential induced by direct spinal cord stimulation (Sp-SCEP) had developed as an alternative option of SEP. Sp-SCEP was safe, stable, and reliable monitoring and was easily combined with TcMEP (25–27). D-wave was the potential directly recorded from the spinal cord by the epidural electrode induced by transcranial stimulation and had also developed as a more stable option for TcMEP. In surgery of 57 IMSCTs, mIONM with TcMEP, SEP, and D-wave was the significant predictive factor of postoperative motor dysfunction (area under the curve (AUC) 0.98) and D-wave was more significant than Tc-MEP or SEP (28).

While MEP or D-wave was proved to be the most significant predictive factor of postoperative motor dysfunction, mIONM with TcMEP and Sp-SCEP was performed in our series instead of D-wave. D-wave could only evaluate the motor function and could not indicate the worsening side. While Sp-SCEP was stable in our series, it was not helpful to predict postoperative motor dysfunction.

In this study, deterioration of McCormick score at the final follow-up was significantly related to the length of peritumoral edema regardless of neither underlying disease, such as diabetes mellitus, nor the size or location of the tumors. Rajshekhar et al. conducted the prospective study and reported that preoperative neurological severity (Nurick grade), preoperative motor function, possible MEP monitoring were the most significant predictive factors for a favorable outcome at discharge

TABLE 3 | Results of logistic regression analyses regarding the preservation of motor function at the final follow-up and the Akaike Information Criterion (AIC) values.

Variable	Estimate	*P* value	OR	95%CI	
Drinking	−16.39	0.0639	7.613821E-08	2.008602E-21	4.453208E-02
Hyperlipidemia	−19.15	0.1267	4.85E-09	5.37E-22	7.00E-03
Hypertension	2.08	0.3306	8.032087E+00	1.11E-01	1.18E+03
Preoperative motor weakness at MMT	−11.62	0.062	8.97E-06	3.38E-13	4.20E-02
Change of MEP	−11.49	0.0374*	1.02E-05	9.210130E-12	2.94E-02
Smoking	17.33	0.0618	3.36E+07	9.127656E+01	7.15E+18
					AIC=24.7

**Means "the difference is statistically significant".*

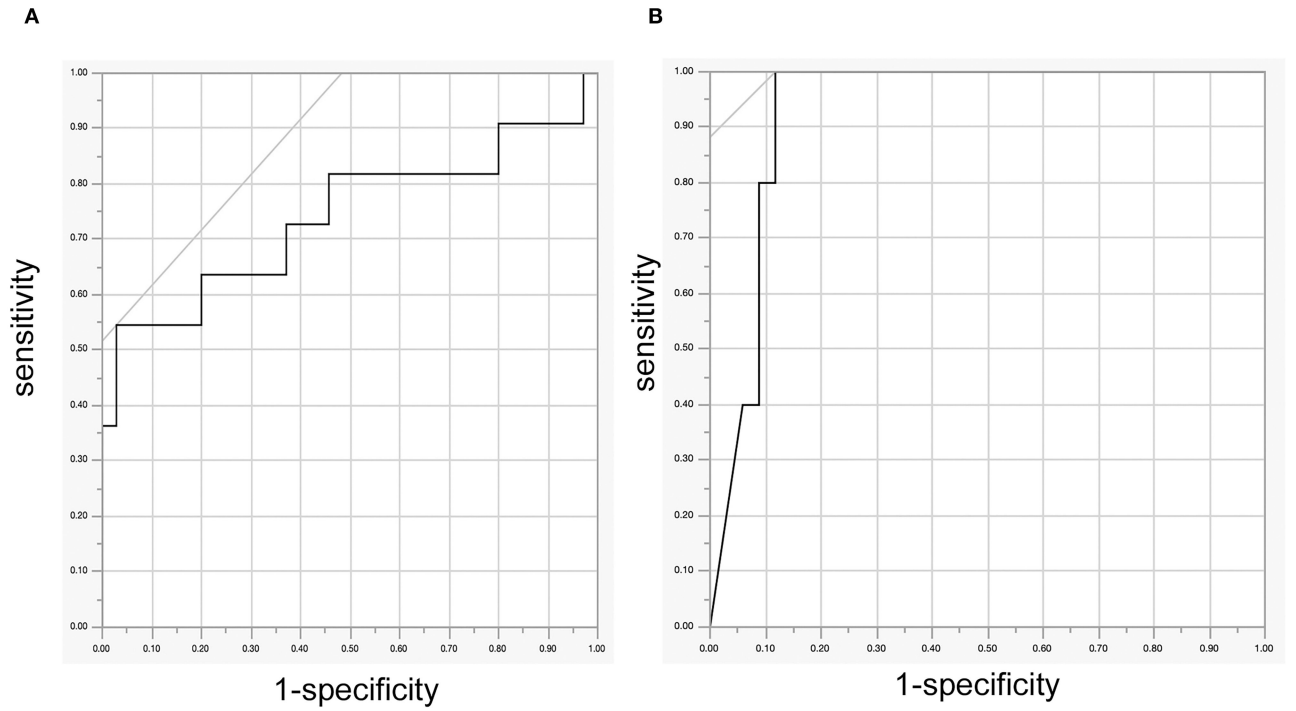

FIGURE 1 | (A) ROC curve between the Ratio motor-evoked potential (MEP) and the deterioration of the motor function of 46 extremities 2 weeks after surgery, **(B)** ROC curve between Ratio MEP and the deterioration of the motor function of 46 extremities at the final follow-up. ROC, receiver operating characteristic.

(29). We could not show that Ratio MEP was significantly related to a favorable postoperative McCormick score probably because the number of patients in this study was quite small and we used McCormick score instead of Nurick grade. Some reported MEP monitoring could significantly improve McCormick's scores (21), others showed that MEP could increase the gross total resection rate but not affect postoperative McCormick score (12). It is still controversial whether MEP monitoring can significantly affect McCormick score at the final follow-up after spinal tumor surgery.

Park et al. examined the change of MEP on the deterioration of the motor function of 86 muscles in surgery of spinal ependymoma. When they used the cutoff ratio of 0.5, 97.4% of the muscles exhibiting postoperative weakness were recovered during the follow-up. They recommended all or none method of the cutoff value of zero in the evaluation of MEP (30). We performed a statistical analysis of the motor function of 46 muscles, Ratio MEP was the only significant negative factor predicting the deterioration at the final follow-up. In addition, ROC analysis revealed that Ratio MEP was significantly related to the deterioration at the final follow-up with the cutoff value of 0.23. By using this cutoff value, sensitivity, specificity, positive predictive value, and negative predictive value were 100, 88, 100, and 88%, respectively, which were quite high.

Muramoto et al. performed the same ROC analysis of 280 muscles in 37 patients who received surgery of intramedullary spinal tumor. This is the only study with a detailed ROC analysis to determine the cutoff value of MEP. Motor function of 51 muscles in 13 patients had deteriorated. Their estimated cutoff value of Ratio MEP was 0.12. Sensitivity, specificity, positive

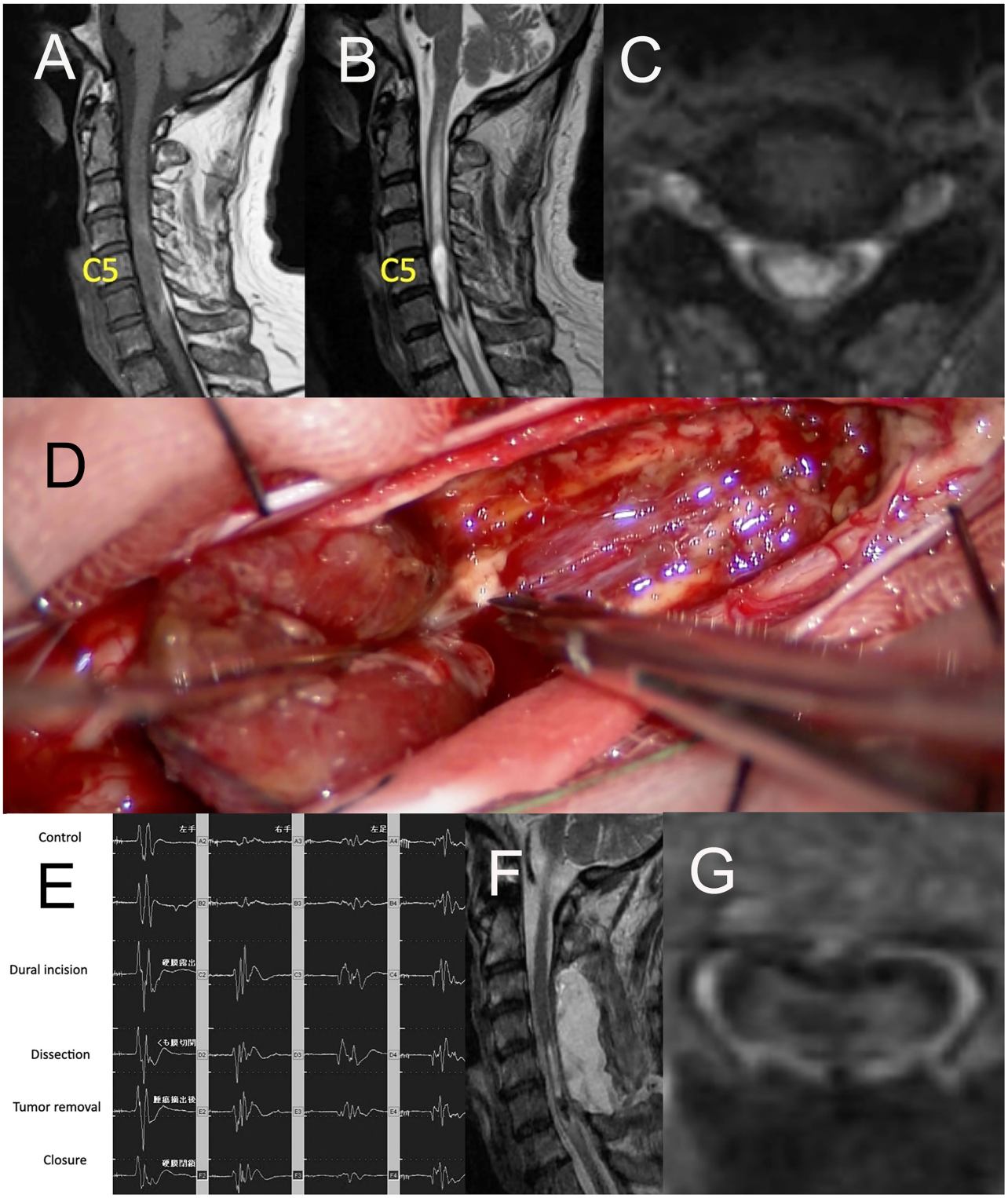

FIGURE 2 | (A) Sagittal image of preoperative Gd-enhanced T1WI of MRI, **(B)** the axial image of preoperative T2WI of MRI, **(C)** the axial image of preoperative Gd-enhanced T1WI of MRI, **(D)** intraoperative photograph of tumor resection through midline myelotomy by posterior approach, **(E)** Ratio motor-evoked potential (MEP) of both UE and LE ranged from 91 to 108%, **(F)** Sagittal image of postoperative Gd-enhanced T1WI of MRI, **(G)** the axial image of postoperative Gd-enhanced T1WI of MRI. Gd, gadolinium; TIWI, T1-weighted image; MRI, magnetic resonance imaging; T2WI, T2-weighted image; UE, upper extremity; LE, lower extremity.

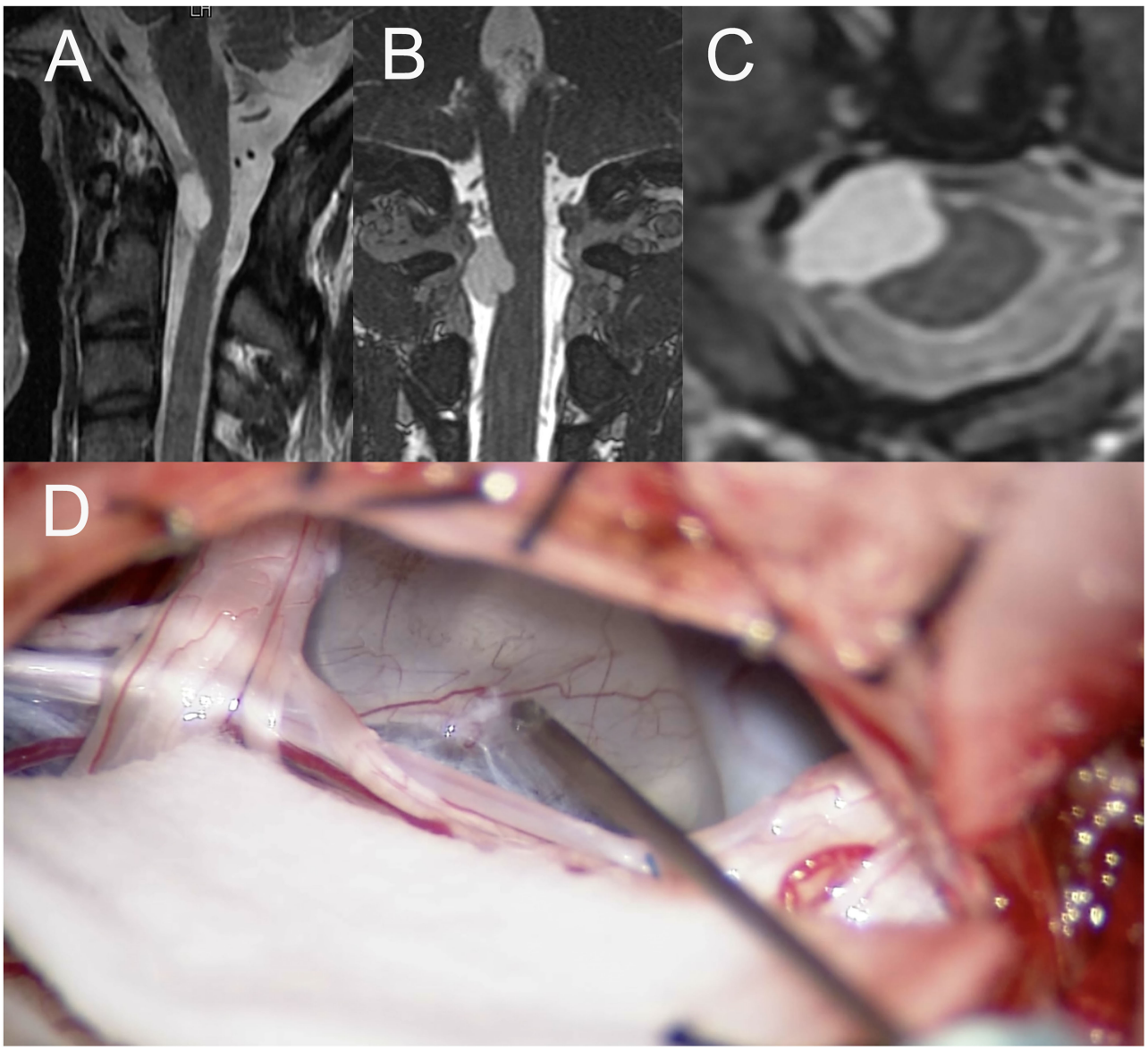

FIGURE 3 | (A) Sagittal image of preoperative T1WI of MRI, **(B)** the coronal image of preoperative T1WI of MRI, **(C)** the axial image of preoperative Gd-enhanced T1WI of MRI, **(D)** intraoperative photograph of tumor resection by posterior approach. TIWI, T1-weighted image; MRI, magnetic resonance imaging; T2WI, T2-weighted image, Gd, gadolinium.

predictive value, and negative predictive value were 86, 74, 88, and 78%, which seemed lower than our study (31). While we used only one muscle at each extremity for MEP monitoring, they examined multiple muscles in each extremity. The difference in the results between the two studies might be caused by the difference in the way of MEP monitoring and of the number of muscles at one extremity. The cutoff value might be different depending on the institutions.

Milicevic examined the effect of IONM on the extent of tumor resection of 39 IMSCTs. Gross total resection was achieved in 89.7% but was not influenced by IONM (32). Cofano also reported that gross total resection was achieved in 84.3% of 249 IMSCTs and the use of IONM significantly affected the clinical condition at follow-up but not at discharge. However, the extent of resection was not associated with the use of IONM (33). van der Wal examined the effect of IONM for surgery of 78 EMSCTs. Total resection was achieved in 70.5% and mIONM with TcMEP and SEP yielded high to perfect sensitivity and high specificity for prediction of the deterioration of McCormick scores. van der Wal also mentioned that monitoring did not always determine the extent of resection because of surgeons' overruling of IONM. When the signal of IONM decreases, the surgeon temporarily stops resecting but usually proceeds resection with more caution or changes the dissecting plane (23). The resection strategy

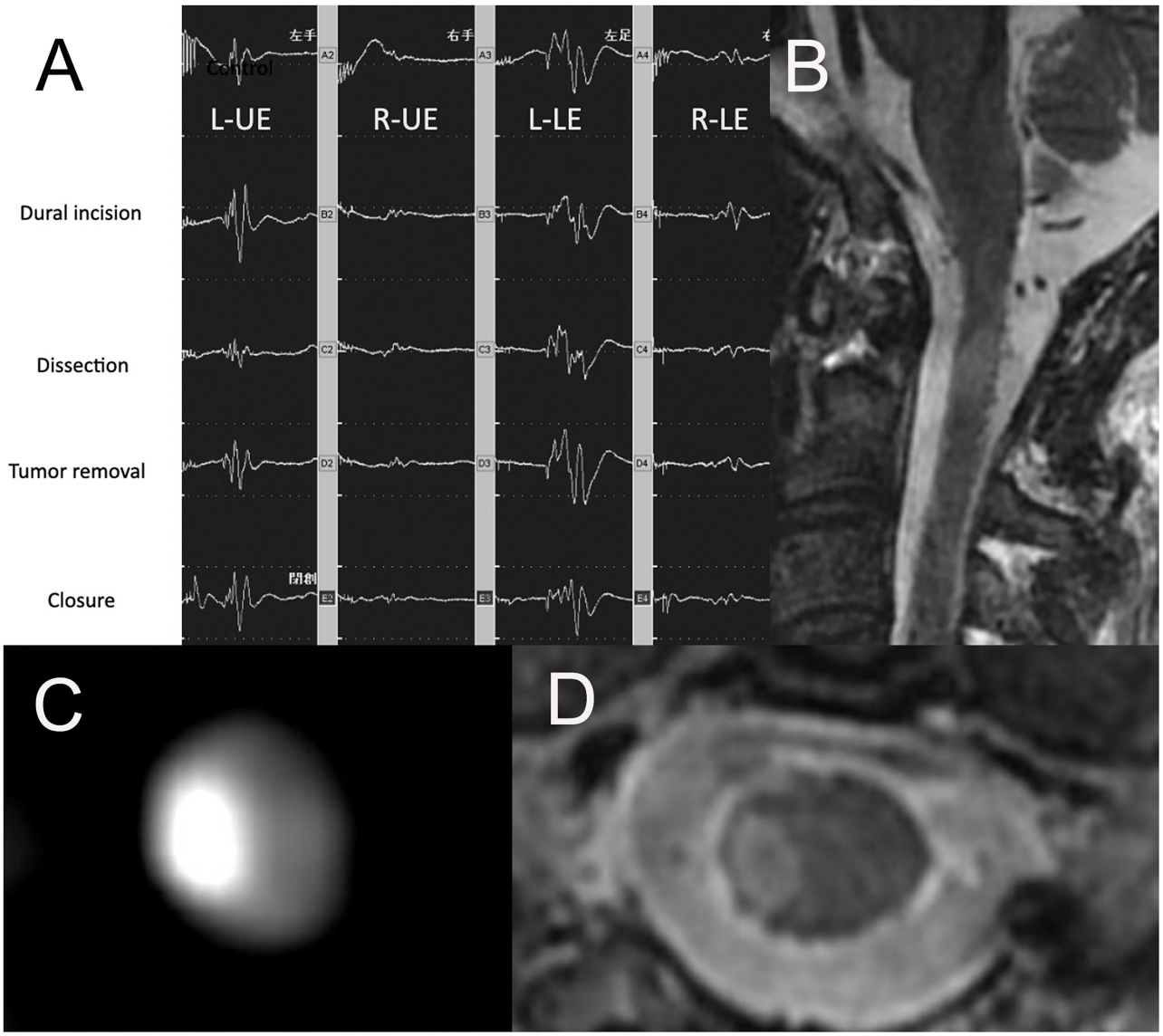

FIGURE 4 | (A) Ratio motor-evoked potential (MEP) of right UE and right LE suddenly reached down to 0 and 30% compared to the initial value, **(B)** the sagittal image of postoperative T1WI of MRI, **(C)** the axial image of postoperative DWI of MRI, **(D)** the axial image of postoperative FLAIR of MRI. UE, upper extremity; LE, lower extremity; TIWI, T1-weighted image; MRI, magnetic resonance imaging; T2WI, T2-weighted image; DWI, diffusion-weighted imaging; FLAIR, fluid-attenuated inversion recovery.

also depends on the nature of the tumor (23). In surgery for 500 IMSCTs, complete resection could be achieved in 77.2% of defined tumors and 41.7% of diffuse tumors even by the implementation of IONM with MEP (13).

In this study, we achieved gross total resection in 13 of 14 patients. In Case 2, MEP of the right upper and right lower extremities almost disappeared just after the dural incision. The tumor was tightly adhered to the spinal cord. In spite that Ratio MEP of this patient reached less than 0.23, we continued tumor resection to achieve subtotal resection. MEP did not recover until the end of the surgery. The patient showed left hemiparesis and hemihypesthesia but recovered to be able to walk and returned to work. However, the ratio of Sp-SCEP was also reduced to 0.33 in this case. If both of mIONM waned about postoperative deterioration, we might stop resection, especially in surgery of diffuse, malignant tumor, or tumor with severe adhesion.

CONCLUSIONS

Ratio MEP was the most significant negative factor that predicts deterioration of motor weakness at spinal tumor surgery. The setting of the cutoff value should be more strict as compared to the brain surgery and might be different depending on the institutions. If both of mIONMs waned about postoperative deterioration, we might stop resection, especially in surgery of diffuse, malignant tumor, or tumor with severe adhesion.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by 20200080. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SY and KK: concept, design, and analysis and interpretation of data. HA: study supervision. KK: statistical analysis. TK: critically revising the article. SK, MI, TY, AK, MK, YS, HU, YT, and RH: acquisition of data. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsurg.2022.883832/full#supplementary-material

Supplementary Video 1 | Cervical ependymoma without abnormal findings on MEP.

Supplementary Video 2 | Tumor with neurenteric cyst with MEP signals suddenly disappearing during surgery.

REFERENCES

1. Elsberg CA. *Diagnosis and Treatment of Surgical Diseases of the Spinal Cord and Its Membranes.* Philadelphia, W. B. Saunders Company (1916).
2. Kopelson G, Linggood RM, Kleinman GM, DoucetteJ, Wang CC. Management of intramedullary spinal cord tumors. *Radiology.* (1980) 135:473–9. doi: 10.1148/radiology.135.2.7367644
3. Yasargil MG, Antic J, Laciga R, de Preux J, Fideler RW, Boone SC. The microsurgical removal of intramedullary spinal hemangioblastomas. Report of twelve cases and a review of the literature. *Surg Neurol.* (1976) 1:141–8.
4. Nuwer MR, Dawson EG, Carlson LG, Kanim LK, Sherman JE. Somatosensory evoked potential spinal cord monitoring reduces neurologic deficits after scoliosis surgery: results of a large multicenter survey. *Electroencephalogr Clin Neurophysiol.* (1995) 96:6–11. doi: 10.1016/0013-4694(94)00235-D
5. Ginsburg HH, Shetter AG, Raudzens PA. Postoperative paraplegia with preserved intraoperative somatosensory evoked potentials. Case report. *J Neurosurg.* (1985) 63:296–300. doi: 10.3171/jns.1985.63.2.0296
6. Kearse LA Jr, Lopez-Bresnahan M, McPeck K, Tambe V. Loss of somatosensory evoked potentials during intramedullary spinal cord surgery predicts postoperative neurologic deficits in motor function [corrected]. *J Clin Anesth.* (1993) 5:392–8. doi: 10.1016/0952-8180(93)90103-L
7. Kitagawa H, Itoh T, Takano H, Takakuwa K, Yamamoto N, Yamada H, et al. Motor evoked potential monitoring during upper cervical spine surgery. *Spine.* (1989) 10:1078–83. doi: 10.1097/00007632-198910000-00009
8. Dennis GC, Dehkordi O, Millis RM, Cole AN, Brown DS, Paul OA. Monitoring of median nerve somatosensory evoked potentials during cervical spinal cord decompression. *J Clin Neurophysiol.* (1996) 13:51–9. doi: 10.1097/00004691-199601000-00005
9. Iwasaki H, Tamaki T, Yoshida M, Ando M, Yamada H, Tsutsui S, et al. Efficacy and limitations of current methods of intraoperative spinal cord monitoring. *J Orthop Sci.* (2003) 8:635–42. doi: 10.1007/s00776-003-0693-z
10. Morota N, Deletis V, Constantini S, Kofler M, Cohen H, Epstein FJ. The role of motor evoked potentials during surgery for intramedullary spinal cord tumors. *Neurosurgery.* (1997) 41:1327–36. doi: 10.1097/00006123-199712000-00017
11. Quiñones-Hinojosa A, Lyon R, Zada G, Lamborn KR, Gupta N, Parsa AT, et al. Changes in transcranial motor evoked potentials during intramedullary spinal cord tumor resection correlate with postoperative motor function. *Neurosurgery.* (2005) 56:982–93.
12. Choi I, Hyun SJ, Kang JK, Rhim SC. Combined muscle motor and somatosensory evoked potentials for intramedullary spinal cord tumour surgery. *Yonsei Med J.* (2014) 55:1063–71. doi: 10.3349/ymj.2014.55.4.1063
13. Westphal M, Mende KC, Eicker SO. Refining the treatment of spinal cord lesions: experience from 500 cases. *Neurosurg Focus.* (2021) 50:E22. doi: 10.3171/2021.2.FOCUS201107
14. Ruschel LG, Aragão A, de Oliveira MF, Milano JB, Neto MC, Ramina R. Correlation of intraoperative neurophysiological parameters and outcomes in patients with intramedullary tumors. *Asian J Neurosurg.* (2021) 16:243–8. doi: 10.4103/ajns.AJNS_234_20
15. Krammer MJ, Wolf S, Schul DB, Gerstner W, Lumenta CB. Significance of intraoperative motor function monitoring using transcranial electrical motor evoked potentials (MEP) in patients with spinal and cranial lesions near the motor pathways. *Br J Neurosurg.* (2009) 23:48–55. doi: 10.1080/02688690802563349
16. Tanaka S, Tashiro T, Gomi A, Takanashi J, Ujiie H. Sensitivity and specificity in transcranial motor-evoked potential monitoring during neurosurgical operations. *Surg Neurol Int.* (2011) 2:111. doi: 10.4103/2152-7806.83731
17. Kurokawa R, Kim P, Itoki K, Yamamoto S, Shingo T, Kawamoto T, et al. False-positive and false-negative results of motor evoked potential monitoring during surgery for intramedullary spinal cord tumors. *Oper Neurosurg (Hagerstown).* (2018) 14:279–87. doi: 10.1093/ons/opx113
18. Kimchi G, Knoller N, Korn A, Eyal-Mazuz Y, Sapir Y, Peled A, et al. Delayed variations in the diagnostic accuracy of intraoperative neuromonitoring in the resection of intramedullary spinal cord tumors. *Neurosurg Focus.* (2021) 50:E21. doi: 10.3171/2021.2.FOCUS201084
19. Hyun SJ, Rhim SC. Combined motor and somatosensory evoked potential monitoring for intramedullary spinal cord tumor surgery: correlation of clinical and neurophysiological data in 17 consecutive procedures. *Br J Neurosurg.* (2009) 23:393–400. doi: 10.1080/02688690902964744
20. Chang SH, Park YG, Kim DH, Yoon SY. Monitoring of motor and somatosensory evoked potentials during spine surgery: intraoperative changes and postoperative outcomes. *Ann Rehabil Med.* (2016) 40:470–80. doi: 10.5535/arm.2016.40.3.470
21. Kang H, Gwak HS, Shin SH, Woo MK, Jeong IH, Yoo H, et al. Monitoring rate and predictability of intraoperative monitoring in patients with intradural extramedullary and epidural metastatic spinal tumors. *Spinal Cord.* (2017) 55:906–10. doi: 10.1038/sc.2017.43
22. Sala F, Palandri G, Basso E, Lanteri P, Deletis V, Faccioli F, et al. Motor evoked potential monitoring improves outcome after surgery for intramedullary

spinal cord tumors: a historical control study. *Neurosurgery.* (2006) 58:1129–43. doi: 10.1227/01.NEU.0000215948.97195.58
23. van der Wal EC, Klimek M, Rijs K. Scheltens-de Boer M, Biesheuvel K, Harhangi BS: Intraoperative neuromonitoring in patients with intradural extramedullary spinal cord tumor: a single-center case series. *World Neurosurg.* (2021) 147:e516–23. doi: 10.1016/j.wneu.2020.12.099
24. Lee S, Cho DC, Rhim SC, Lee BJ, Hong SH, Koo YS, et al. Intraoperative monitoring for cauda equina tumors: surgical outcomes and neurophysiological data accrued over 10 years. *Neurospine.* (2021) 18:281–9. doi: 10.14245/ns.2040660.330
25. Ando M, Tamaki T, Yoshida M, Kawakami M, Kubota S, Nakagawa Y, et al. Intraoperative spinal cord monitoring using combined motor and sensory evoked potentials recorded from the spinal cord during surgery for intramedullary spinal cord tumor. *Clin Neurol Neurosurg.* (2015) 133:18–23. doi: 10.1016/j.clineuro.2015.03.004
26. Koyanagi I, Iwasaki Y, Isu T, Abe H, Akino M, Kuroda S. Spinal cord evoked potential monitoring after spinal cord stimulation during surgery of spinal cord tumors. *Neurosurgery.* (1993) 33:451–9. doi: 10.1227/00006123-199309000-00015
27. Duffau H, Capelle L, Sichez J. Direct spinal cord electrical stimulations during surgery of intramedullary tumoral and vascular lesions. *Stereotact Funct Neurosurg.* (1998) 4:180–9. doi: 10.1159/000029662
28. Cannizzaro D, Mancarella C, Nasi D, Tropeano MP, Anania CD, Cataletti G, et al. Intramedullary spinal cord tumors: the value of intraoperative neurophysiological monitoring in a series of 57 cases from two Italian centres. *J Neurosurg Sci.* (2019). doi: 10.23736/S0390-5616.19.04758-1
29. Rajshekhar V, Velayutham P, Joseph M, Babu KS. Factors predicting the feasibility of monitoring lower-limb muscle motor evoked potentials in patients undergoing excision of spinal cord tumors. *J Neurosurg Spine.* (2011) 14:748–53. doi: 10.3171/2011.1.SPINE10310
30. Park JH, Lee SH, Kim ES, Eoh W. Analysis of multimodal intraoperative monitoring during intramedullary spinal ependymoma surgery. *World Neurosurg.* (2018) 120:e169–80. doi: 10.1016/j.wneu.2018.07.267
31. Muramoto A, Imagama S, Ito Z, Ando K, Tauchi R, Matsumoto T, et al. The cutoff amplitude of transcranial motor evoked potentials for transient postoperative motor deficits in intramedullary spinal cord tumor surgery. *Spine.* (2014) 39:E1086–94. doi: 10.1097/BRS.0000000000000421
32. Milicevic M, Solari D, Illic R, Frio F, Stanimirovic A, Savic D, et al. The impact of intraoperative monitoring on extent of resection and long-term neurological outcomes: a series of 39 intramedullary ependimomas. *Turk Neurosurg.* (2020) 30:252–62. doi: 10.5137/1019-5149.JTN.27471-19.2
33. Cofano F, Giambra C, Costa P, Zeppa P, Bianconi A, Mammi M, et al. Management of extramedullary intradural spinal tumors: the impact of clinical status, intraoperative neurophysiological monitoring and surgical approach on outcomes in a 12-year double-center experience. *Front Neurol.* (2020) 11:598619. doi: 10.3389/fneur.2020.598619

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Clinical Evaluation of Paraspinal Mini-Tubular Lumbar Decompression and Minimally Invasive Transforaminal Lumbar Interbody Fusion for Lumbar Spondylolisthesis Grade I with Lumbar Spinal Stenosis: A Cohort Study

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Objective: To investigate the clinical outcome data and difference in efficacy between paraspinal mini-tubular lumbar decompression (PMTD) and minimally invasive transforaminal lumbar interbody fusion (MIS TLIF) in the treatment of degenerative lumbar spondylolisthesis grade I with lumbar spinal stenosis (DLS-I-LSS).

Methods: Patients with DLS-I-LSS, who underwent PMTD or MIS TLIF from September 2017 to March 2020, were included retrospectively. The follow-up period was 24 months after surgery. Outcome measurements included the Oswestry disability index (ODI) score, visual analog scale (VAS) low back pain score, VAS leg pain score, surgical data, and adverse events.

Results: A total of 104 patients with DLS-I-LSS were included in this study. The average improvement in ODI at 12 months (2.0%, 95% CI, −5.7% to 1.8%; $p = 0.30$) and 24 months (1.7%, 95% CI, −2.7% to 6.1%; $p = 0.45$) after surgery between the two groups were not statistically significant. The improvement in VAS low back pain score after 24 months and improvement in VAS leg pain score were not significantly different between the two groups. Compared with the PMTD group, the MIS TLIF group had more estimated blood loss and longer hospital stays. The cumulative reoperation rates were 5.66% and 1.96% in the MIS TLIF and PMTD groups, respectively ($p = 0.68$). The results of multivariate analysis showed that BMI, diabetes, and baseline ODI score were the main factors influencing the improvement in ODI in patients with DLS-I-LSS after minimally invasive surgery, accounting for 50.5% of the total variance.

Conclusions: The clinical effectiveness of PMTD was non-inferior to that of MIS TLIF for DLS-I-LSS; however, there was a reduced duration of hospital stay, operation time, blood loss, and hospitalization costs in the PMTD group. BMI, presence or absence of diabetes

and baseline ODI score were influencing factors for the improvement of ODI (Trial Registration: ChiCTR2000040025).

Keywords: degenerative lumbar spondylolisthesis, paraspinal mini-tubular lumbar decompression, minimally invasive transforaminal lumbar interbody fusion, lumbar spinal stenosis, minimally invasive spine surgery

INTRODUCTION

Degenerative lumbar spondylolisthesis (DLS) is a spine disease that results in lower back pain (1–3). Patients with symptomatic lumbar spondylolisthesis may begin with conservative treatment strategies and physical rehabilitation training, including constrained motion, epidural steroid injection, and electrophotoluminescence (4–7). Surgical management is recommended in patients who fail conservative treatment strategies (6, 8). Decompression or decompression with fusion are the two main surgical options for DLS (9, 10). Recent evidence suggests that surgical treatment for DLS is superior to nonsurgical treatment (11, 12).

The main goal of surgery is to decompress the central canal, lateral recess, and nerve foramen for lumbar spinal stenosis associated with DLS (4). At present, whether additional internal fixation fusion should be performed after decompression in patients with degenerative lumbar spondylolisthesis grade I with lumbar spinal stenosis (DLS-I-LSS) remains controversial. In 2016, two prospective randomized controlled clinical studies of DLS-I-LSS were published in the New England Journal of Medicine. Forsh et al. (13) found that the effect of decompression with fusion was not better than that of decompression alone. However, Ghogawala et al. (14) indicated that decompression with fusion was superior to decompression alone. After combining the results of the two studies, decompression alone in the treatment of DLS-I-LSS may be as effective as decompression with fusion. At present, the most common surgical approach for lumbar spinal decompression is posterior midline laminectomy assisted microscopically (15).

In 1997, Foley and Smith independently reported the first microendoscopic discectomy (16). In 2002, Greiner-Perth et al. (17) reported the use of a microscope in combination with a channel system to address two-dimensional visual fields for the treatment of lumbar disc herniation (LDH). In China, Chunmei et al. (18, 19) were the first to combine a microscope with a microtube working system using a paraspinal approach to achieve bilateral decompression via a unilateral approach. Thus, the efficacy and safety of paraspinal mini-tubular lumbar decompression (PMTD) for the treatment of lumbar spinal stenosis were verified. Compared with the traditional posterior midline approach for spinal decompression, the surgical approach of PMTD is a paravertebral interlaminar approach, which preserves the integrity of the spinal muscles and ligaments based on expansion and blunt muscle separation. Therefore, PMTD has the potential to be as effective as decompression with fusion for patients with DLS-I-LSS (20).

Transforaminal lumbar interbody fusion (TLIF) is the most commonly used surgical procedure for nerve decompression and bone stabilization (21–24). Minimally invasive transforaminal lumbar interbody fusion (MIS TLIF) may result in spinal cord decompression and intervertebral fusion based on a mini-tubular approach and percutaneous pedicle screw placement (25–28).

At present, PMTD and MIS-TLF have been widely used for the treatment of DLS-I-LSS (29, 30). However, differences in efficacy and safety between the two surgical procedures have not been reported. This ambidirectional cohort study aimed to investigate the difference between PMTD and MIS TLIF in the treatment of DLS-I-LSS.

MATERIALS AND METHODS

Patient Population

This ambidirectional cohort study was conducted at Fujian Medical University Union Hospital. After obtaining approval from the ethics board at Fujian Medical University Union Hospital (Ethics Approval Number, 2020KY0134) and registering the study at the Chinese Clinical Trial Registry (Clinical Study Registration Number, http://www.chictr.org.cn/, ChiCTR2000040025), we reviewed all patients with DLS-I-LSS who received PMTD or MIS TLIF performed by a spine neurosurgeon from September 2017 to March 2020. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) recommendations were strictly followed in the reporting of this comparative study (31). The diagnostic criteria were as follows: (1) typical clinical manifestations: low back pain, leg pain, and intermittent claudication; (2) lumbar radiographs indicated grade I lumbar spondylolisthesis (according to the Meyerding classification (32)); (3) lumbar spondylolisthesis and lumbar spinal stenosis were confirmed by MRI and CT in all patients, and the stenosis location was consistent with the corresponding neurological symptoms. The inclusion and exclusion criteria are listed in **Table 1**.

Patients were allocated to the PMTD or MIS TLIF group according to the actual conditions of the surgical procedure.

Intervention: PMTD

After the target segment was located based on intraoperative fluoroscopy, a paraspinal incision (1.5–1.8 cm) was made, and the subcutaneous tissue and fascia were cut separately. The trocar and sequential tubular retractors will be placed paraspinally, under fluoroscopic control. The soft tissue on the surface of the lamina was bluntly separated step by step, and the lower margin of the lamina and spinous processes on the affected side of the upper vertebral body of the target segment was removed using a microdrill. After the ligamentum flavum was resected, the dura was fully exposed, and ipsilateral and

TABLE 1 | Inclusive and exclusive criteria.

Inclusive criteria
Age between 30 and 70 years
Typical clinical manifestations (eg. low back pain, leg pain, and intermittent claudication) with failed conservative treatment at least 3 months
Grade I lumbar spondylolisthesis (according to the Meyerding classification)
Symptoms are confirmed by CT and MRI, and matches the affected segment
Without lumbar instability
Received PMTD or MIS-TLIF
Exclusive criteria
Previous surgery on the same or adjacent segment
Multiple spondylolisthesis
Other serious physical, psychological or mental diseases
Currently participating in other clinical trials
Similar symptoms that caused by severe somatic or psychiatric illness
With a history of spinal cord injury/trauma
Cauda equina syndrome

Preoperative hyperextension and flexion radiographs showed an angle difference of less than 10° between the upper and lower endplates of the affected segments or a transitional distance of less than 3 mm between the vertebral bodies.

contralateral decompression was performed (**Figures 1A–1D**). If necessary, the protruding or prolapsed nucleus pulposus tissue and some intervertebral nucleus pulposus were removed.

Intervention: MIS TLIF

With fluoroscopic assistance, blunt separation was performed to expose the lamina and facet joints through the Wiltse space (33). The paraspinal tubular retractors were inserted, with the assistance of a microscope, the intervertebral disc tissue was fully processed, the osteophytes and hyperplasia soft tissue lesions of nerve compression were completely removed, the nerve root canal and lateral fossa were further expanded, and the compressors causing nerve root compression were completely removed. A similar procedure was performed on the other side if the same compression existed. An autologous bone fragment and an appropriate cage fusion device were implanted into the intervertebral space (**Figures 1E,F**).

Outcome Measurement and Data Collection

Baseline information including sex, age, body mass index (BMI), comorbidities, ASA grade (34), target segment, clinical performance, duration of symptoms, relative slip distance of the vertebral body, preoperative Oswestry disability index (ODI) (35), and preoperative visual analog scale (VAS) (36) of the back and leg were collected to compare the baseline consistency between the two groups. The baseline and postoperative ODI, and baseline and postoperative VAS scores at 12 and 24 months were collected to compare the clinical efficacy. The VAS difference (i.e., ΔVAS) means the pre-operative VAS scores minus the final VAS scores. And The ODI difference (i.e., ΔODI) means the pre-operative ODI scores minus the final ODI scores. Surgical time, blood loss,

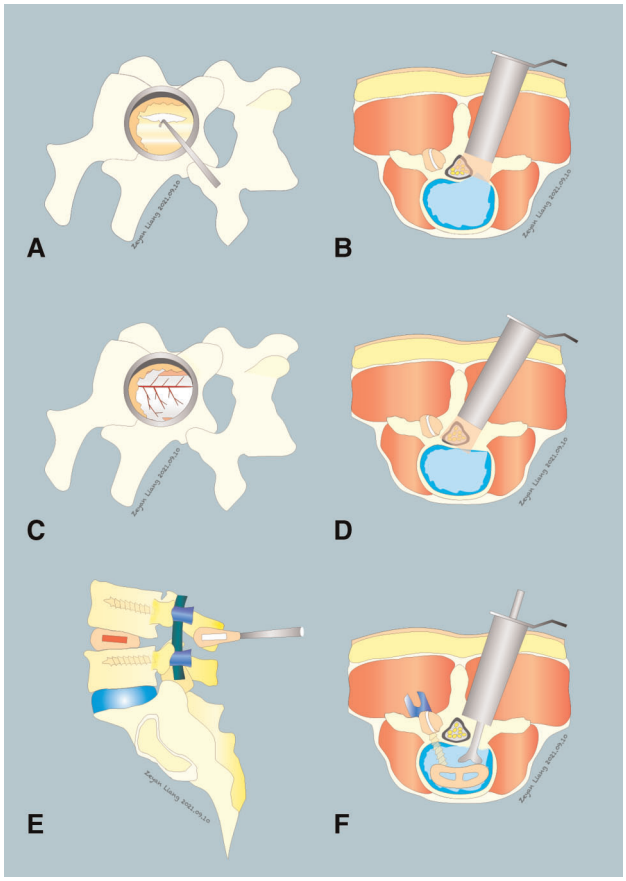

FIGURE 1 | Comparison of PMTD and MIS TLIF Techniques. PMTD: (**A**) insertion of a nerve hook to start dissection of the ligamentum flavum (LF). (**B**) completing the ipsilateral decompression. (**C,D**) a complete removal of the LF is achieved and the dura is safely exposed. The contralateral exiting and traversing nerve roots may also be exposed if necessary. MIS TLIF: (**E,F**) an L4–5 MIS TLIF, a surgical option that includes a fusion procedure in addition to decompression.

length of incision, duration of hospital stay, hospitalization costs, incision infection, healing of operative incision, reoperation, and postoperative lumbar instability were used to compare clinical safety. Lumbar stability was defined postoperative hyperextension and flexion radiographs showed an angle difference of less than 10° between the upper and lower endplates of the affected segments or a transitional distance of less than 3 mm between the vertebral bodies.

Statistical Analysis

Continuous variables are represented as mean ± standard deviation, and binomial distribution variables are expressed by frequency. An independent sample t-test was used to compare two sets of data that followed a normal distribution; otherwise, the Wilcoxon rank-sum test was used. Counting data were examined and analyzed using Chi-square nonparametric analysis. A p-value <0.05 indicated that the difference was statistically significant. For multivariate

analyses, multivariate linear regression models were fitted for changes in ODI scores at 24 months (i.e., 24-month value - baseline value). All data were analyzed using SPSS 22.0.

Sample Size

For the primary outcome, choosing a 5% noninferiority margin, a type 1 error of 0.05, and power of 0.80 gave a total sample size of 94 (20).

Patient and Public Involvement

It was not appropriate or possible to involve patients or the public in the design, or conduct, or reporting, or dissemination plans of our research.

RESULTS

A total of 104 patients with DLS-I-LSS were included in this study after screening based on inclusion and exclusion criteria. Fifty-three patients underwent PMTD, while the others underwent MIS TLIF. **Figure 2** shows a flow chart of this study. The clinical data of patients who underwent PMTD or MIS TLIF for DLS-I-LSS were retrospectively collected at 12 months and prospectively collected at 12 to 24 months. The characteristics of the patients in the PMTD and MIS TLIF groups are shown in **Table 2**. There was a comparable equilibrium between the two groups ($p > 0.05$).

Oswestry Disability Index

In terms of ODI score, compared with PMTD (mean [SD] %, 45.73 [9.08]%), the ΔODI score of the MIS TLIF group at 12 months was 47.68 [10.13]%. The ΔODI score was 47.93 [10.52]% in the PMTD and 46.26 [10.05]% in the MIS TLIF group at 24 months. No significant differences were observed between the two groups at 12 months (PMTD minus MIS TLIF, 2.0%, 95% CI, −5.7% to 1.8%; $p = 0.30$) and 24 months (PMTD minus MIS TLIF, 1.7%, 95% CI, −2.7% to 6.1%; $p = 0.45$, **Table 3**). The postoperative ODI scores of both PMTD and MIS TLIF were significantly better than those before surgery ($p = 0.001$, **Figure 3A**).

Visual Analog Scale

In terms of the ΔVAS lower back pain score at 12 months after surgery, there was no statistically significant difference between the two groups (PMTD minus MIS TLIF, −0.3 cm, 95% CI, −1.3 cm to 0.6 cm; $p = 0.48$; **Table 3**). Considering the ΔVAS lower back pain score at 24 months, the statistical analysis results showed no significant difference (PMTD minus MIS TLIF, −0.3 cm, 95% CI, −1.4 cm to 0.7 cm; $p = 0.55$; **Table 3**).

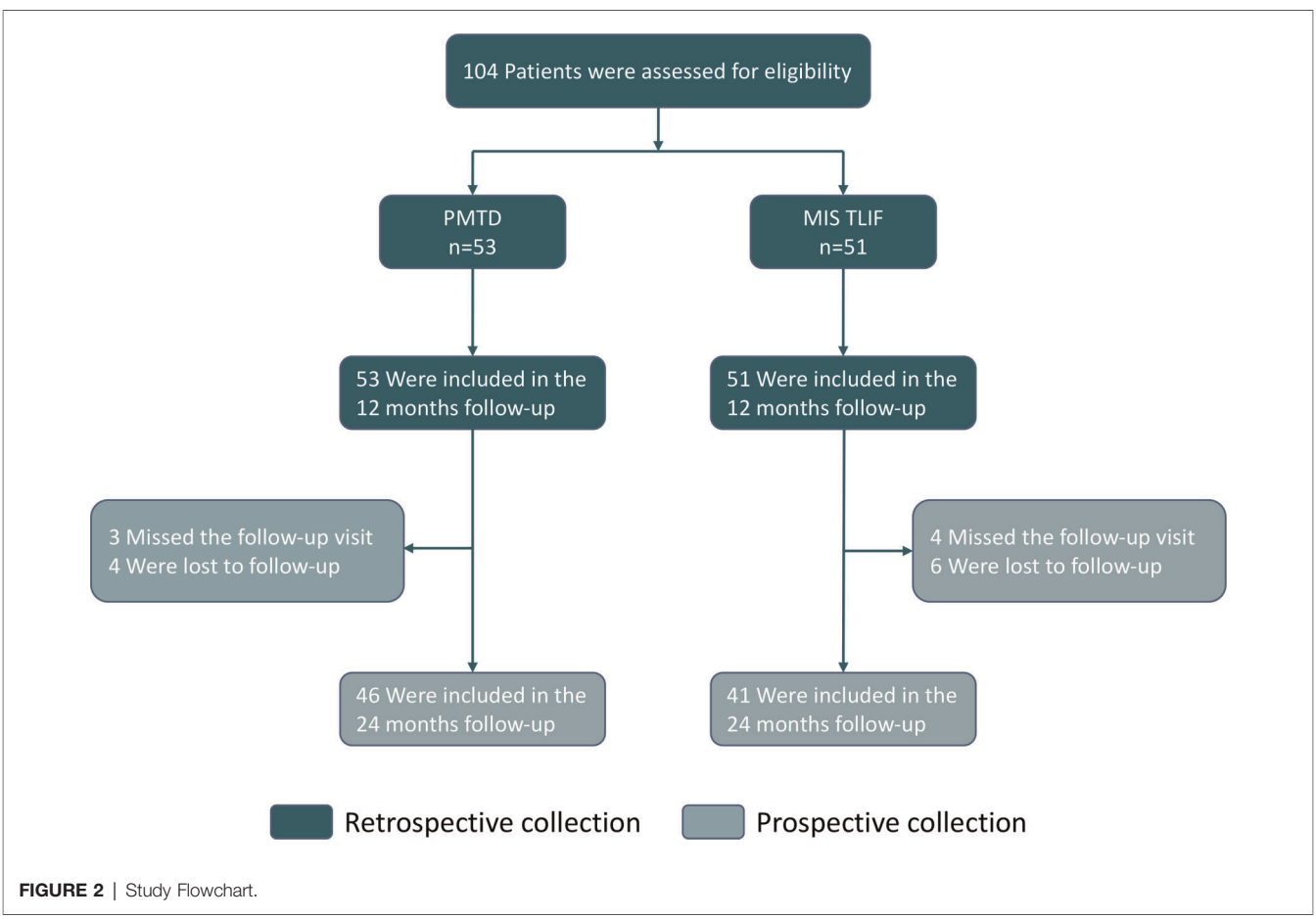

FIGURE 2 | Study Flowchart.

The postoperative VAS lower back pain scores of both PMTD and MIS TLIF were significantly better than those before surgery ($p = 0.001$, **Figure 3B**). Regarding the ΔVAS leg pain score at 12 months (PMTD minus MIS TLIF, −0.8 cm, 95% CI, −1.7 cm to 0.05 cm; $p = 0.06$; **Table 3**) and 24 months (PMTD minus MIS TLIF, −0.3 cm, 95% CI, −1.4 cm to 0.7 cm; $p = 0.55$), statistically significant differences were not observed. The postoperative VAS leg pain scores of both PMTD and MIS TLIF were significantly better than those before surgery ($p = 0.001$, **Figure 3C**).

TABLE 2 | Baseline characteristics of the patients.

Characteristics	PMTD	MIS TLIF	*p* value
Mean age (SD), years	62.06 (13.6)	59.94 (8.3)	0.34
Gender, No. (%)			0.052
Female	26 (50)	34 (67)	NA
Male	27 (50)	17 (33)	NA
Mean BMI (SD), kg/m^2	23.70 (3.5)	24.30 (2.9)	0.34
Smoker, No. (%)	10 (19)	10 (20)	0.56
Comorbidities, No. (%)			
Diabetes mellitus	6 (11)	2 (4)	0.15
Hypertension	15 (28)	14 (28)	0.55
Coronary artery disease	1 (2)	2 (4)	0.49
ASA class III, No. (%)	19 (36)	17 (33)	0.48
Intermittent claudication, No. (%)	17 (32)	22 (43)	0.17
Symptom duration, No. (%)			0.35
<6 mos	4 (8)	6 (12)	NA
>6 mos	49 (92)	45 (88)	NA
Mean degree of vertebral slip (SD), mm	5.94 (2)	6.14 (2)	0.67
Segment underwent surgery, No. (%)			0.34
L3/4	6 (11)	7 (14)	NA
L4/5	40 (76)	32 (63)	NA
L5/S1	7 (13)	12 (23)	NA

NA, no applicable

Surgery Data and Adverse Events

All patients underwent surgery successfully without massive hemorrhage, dural tear, shock, or anesthesia accident during the operation. The operation time (PMTD minus MIS TLIF, −105.5 min, 95% CI, −129.6 min to −81.5 min; $p = 0.001$; **Table 4**), estimated blood loss (−60.2 ml, 95% CI, −76.1 ml to −44.4 ml; $p = 0.001$), length of incision (−4.6 cm, 95% −4.7 cm to −4.5 cm; $p < 0.001$), duration of hospital stay (−4.4 days, 95% CI, −6.0 days to −2.8 days; $p < 0.001$), and hospitalization costs (−33476.0 yuan, 95% CI, −36266.1 yuan to −30685.8 yuan; $p < 0.001$) in the MIS TLIF group were higher than those in the PMTD group, and the differences between the two groups were statistically significant. The adverse events were observed in the follow-up period, including incision infection, operative incision of healing, reoperation and lumbar instability. There were no statistically significant differences between two groups ($p > 0.05$, **Table 4**). The cumulative reoperation rates were 5.66% and 1.96% in the MIS TLIF and PMTD groups, respectively ($p = 0.68$).

Multivariate Analysis

We incorporated surgery types, BMI, diabetes mellitus, degree of vertebral slip, and baseline ODI score into the multivariate analysis model to identify the prognostic factors affecting the efficacy of minimally invasive surgery. According to the multivariate model, BMI ($\beta = -0.96$, 95% CI, −1.4 to −0.48; $p < 0.001$), diabetes mellitus ($\beta = -6.9$, 95% CI, −12.7 to −1.0; $p = 0.022$), and baseline ODI score ($\beta = 0.99$, 95% CI, 0.75 to 1.2; $p < 0.001$) were the predictors of ΔODI score for DLS-I-LSS at 24 months after MISS (**Table 5**). The model with these three variables correctly predicted the response in 50.5% of patients.

TABLE 3 | Changes in ODI score and VAS score from baseline.

Variables	PMTD Group		MIS TLIF Group		Difference (95% CI)	*p* value
	No. of patients	Mean (SD)	No. of patients	Mean (SD)		
ΔODI score						
Preop	53	68.8 (6.0)	51	67.6 (6.4)	1.2 (–1.2, 3.6)	0.32
12 months	53	45.7 (9.1)	51	47.7 (10.1)	–2.0 (–5.7, 1.8)	0.30
24 months	46	47.9 (10.5)	41	46.26 (10.1)	1.7 (–2.7, 6.1)	0.45
ΔVAS low back pain score						
Preop	53	5.6 (3.2)	51	5.80 (3.2)	–0.2 (–1.4, 1.1)	0.79
12 months	53	3.8 (2.5)	51	4.10 (2.4)	–0.3 (–1.3, 0.6)	0.48
24 months	46	4.0 (2.6)	41	4.36 (2.3)	–0.3 (–1.4, 0.7)	0.55
ΔVAS leg pain score						
Preop	53	5.4 (3.0)	51	6.35 (2.9)	–0.9 (–2.1, 0.2)	0.11
12 months	53	3.6 (2.3)	51	4.37 (2.1)	–0.8 (–1.7, 0.05)	0.06
24 months	46	4.2 (2.4)	41	4.54 (2.5)	–0.3 (–1.4, 0.7)	0.55

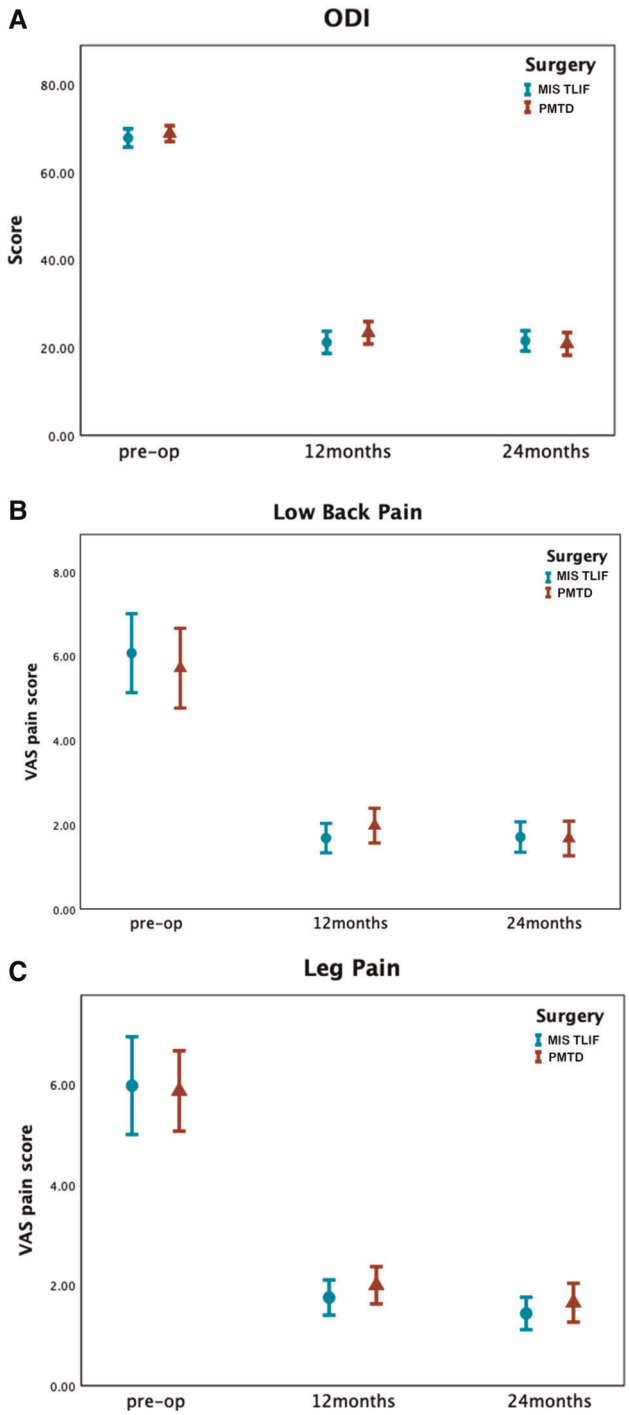

FIGURE 3 | Preoperation, 12-month, and 24-month ODI and VAS following surgery for DLS-I-LSS. (**A**) Average ODI at preoperation, 12 months, and 24 months following surgery, by cohort. (**B**) Average VAS low back pain scores at preoperation, 12 months, and 24 months following surgery, by cohort. (**C**) Average VAS leg pain scores at preoperation, 12 months, and 24 months following surgery, by cohort. For both cohorts there were statistically significant improvements at 12 and 24-month follow-up, relative to preoperation, for ODI, VAS low back pain and VAS leg pain ($p < 0.001$, all comparisons).

TABLE 4 | Surgery data and adverse events.

Variables	PMTD	MIS TLIF	Difference (95% CI)[a]	*p* value
Surgery data				
Mean operation time (SD), mins	191.9 (57.7)	297.43 (65.7)	−105.5 (−129.6, −81.5)	<0.001
Mean estimated blood loss (SD), ml	33.3 (26.9)	93.53 (51.2)	−60.2 (−76.1, −44.4)	<0.001
Mean length of incisions (SD), cm	2.0 (0.10)	6.63 (0.5)	−4.6 (−4.7, −4.5)	<0.001
Mean duration of hospital stay (SD), days	7.5 (3.3)	11.94 (4.9)	−4.4 (−6.0, −2.8)	<0.001
Mean hospitalization costs (SD), yuan[b]	22086.4 (5149.7)	55562.4 (8793.8)	−33476.0 (−36266.1, −30685.8)	<0.001
Adverse events				
Incision infection, No. (%)	0	2 (3.9)	NA	0.14
Operative Incision of Healing, No. (%)	5 (9.4)	7 (13.7)	NA	0.49
Reoperation, No. (%)	3 (5.6)	1 (1.9)	NA	0.68
Postoperative lumbar instability, No. (%)	3 (5.6)	0	NA	0.85

Abbreviation: NA, not applicable.
[a]*Calculated as PMTD minus MIS TLIF with 95% CI.*
[b]*The yuan is the basic unit of the renminbi, which is the official currency of the People's Republic of China.*

TABLE 5 | Significant predictors of 24-month ΔODI score for DLS-I-LSS.[a]

Variables	*β*	95% CI	*p* value
BMI	−0.96	(−1.4, −0.48)	<.001
Diabetes mellitus	−6.9	(−12.7, −1.0)	.022
Baseline ODI score	0.99	(0.75, 1.2)	<.001

[a]*Adjusted* $R^2 = 0.505$.

DISCUSSION

It is now generally believed that lumbar spinal canal decompression and fusion treatment should be used when mobile DLS causes lumbar spine instability and lower back pain (37–39). Controversies remain regarding the surgical treatment of inactive DLS. Studies have shown that pure

lumbar laminectomy may destroy the stability of the lumbar spine (40–42). However, with the development of minimally invasive spine surgery, PMTD technology has been used to treat spinal diseases such as LDH and LSS (18, 19). One of the problems that this study attempts to solve is the pros and cons of minimally invasive lumbar spinal canal decompression technology (i.e., PMTD) and minimally invasive lumbar fusion technology (i.e., MIS TLIF) in the treatment of inactive DLS-I-LSS. This cohort study included 104 patients with DLS-I-LSS to compare the efficacy and safety of PMTD and MIS TLIF. It involves the postoperative ODI score, VAS low back pain score, VAS leg pain score, surgical data, adverse events, and other key outcome indicators.

The VAS was used to assess the degree of lower back pain and leg pain before and after surgery to measure the degree of pain improvement. There was no significant difference in the ΔVAS score of leg pain and ΔVAS score of lower back pain between the PMTD and MIS-TLIF groups at 1 and 2 years after the operation. Therefore, the effects of PMTD technology and MIS-TLIF technology in improving patients with lower back and leg pain are similar. The results of Chan et al. also suggest that microdecompression and decompression plus fuison have similar effects in improving leg pain, while their results suggest that MIS-TLIF technology is better than PMTD technology in improving lower back pain (29). However, in a study by Chan et al. (29), the baseline characteristics of the population between the MIS decompression group and the MIS-TLIF group were inconsistent, which may be one of the reasons for the difference in results. In addition, Liang et al. (43) conducted a meta-analysis study, which included four randomized controlled trials and 13 observational studies, comparing the clinical efficacy of decompression fusion and simple decompression in the treatment of degenerative lumbar spondylolisthesis. The results showed that there was no significant correlation between fusion and improvement in the patients' postoperative lower back pain VAS score and postoperative ODI score. The results of this study also showed that there was no statistically significant difference in ΔODI scores between the PMTD and MIS-TLIF groups at 1 year and 2 years after the operation. Therefore, compared with PMTD, MIS TLIF cannot improve the clinical benefit of patients' symptoms and functional status within 2 years after surgery. In addition, the results of multiple linear regression analysis suggested that BMI, diabetes, and baseline ODI score were the main factors affecting the ΔODI score at 2 years after surgery. The lower ΔODI score in diabetic patients 2 years after surgery may be due to the overlap of the clinical manifestations of peripheral neuropathy and the symptoms of lumbar spondylosis, which reduces the recovery ability of nerve roots after surgery (44–46). Patients with a high BMI had a low degree of postoperative ODI improvement. The randomized controlled spine patient prognosis study trial (SPORT) showed that compared with non-obese patients, the improvement in postoperative ODI score of obese patients was significantly smaller (47). Patients with poor ODI scores at baseline will have the opportunity to achieve the greatest improvement after surgery, because patients with better functional status before surgery may be more susceptible to floor and ceiling effects (48).

Compared with the MIS-TLIF group, the PMTD group had a significantly shorter operation time, less intraoperative blood loss, smaller surgical incisions, shorter postoperative hospital stay, and lower total hospitalization costs. These results are consistent with conclusions of previous research (29, 49, 50). This is because the MIS-TLIF technology requires multiple paravertebral incisions to successfully insert the pedicle screw and bone graft fusion cage; therefore, the surgical incision is large, the amount of bleeding is large, and the fusion and internal fixation materials are involved, resulting in a significant increase in the cost incurred. In the PMTD group, there were three cases of lumbar spine instability occurring within 2 years after surgery and the patients returned to the hospital for internal fixation (one case had a lamina rupture due to a fall, and two cases were caused by a lamina fracture due to weight-bearing during the postoperative recovery period), and one case in the MIS TLIF group (adjacent segment degeneration). However, there was no significant difference in the cumulative reoperation rates between the two groups. Studies have reported that traditional decompression surgery alone has a significantly higher operation rate compared to the fusion group (14). Yavin et al. carried out a meta-analysis and found that there was a correlation between reoperative risk and fusion, which suggested careful patient selection is required (51). Compared with traditional decompression surgery, PMTD uses a paravertebral approach to bluntly separate the muscles, preserve the midline ligaments, and reduce muscle damage, which may reduce reoperation due to instability. Regarding the comparison of incision infection rate, fat liquefaction rate, and postoperative lumbar instability rate, the results were similar between PMTD and MIS TLIF. Based on the analysis of results of all the outcome indicators, the PMTD technique for the treatment of DLS-I-LSS can achieve curative effects similar to those of the MIS-TLIF technique, but it also has the advantages of low cost, short operation time, and a small incision. Therefore, PMTD technology has the potential to become a routine choice for the treatment of DLS-I-LSS.

STUDY LIMITATIONS

This study analyzed in detail the clinical results of PMTD and MIS TLIF in the treatment of DLS-I-LSS, but there are still several limitations. (1) Although there was no significant difference in the baseline characteristics of patients between the PMTD group and the MIS-TLIF group, the study was a retrospective cohort study with a low level of evidence; (2) Although follow-ups were carried out for 1 and 2 years after the operation, the early follow-up data of the patients were missing, and early evaluation of the efficacy between the two groups could not be carried out; (3) Unlike MIS-TLIF, PMTD is a non-fusion technique. There are differences in the focus of the two techniques. Although the results of this study demonstrated that there was no significant difference between

the groups two years after surgery, the comparison lacks rigor to some extent because longer follow-up results should be proposed in the future to demonstrate the applicability of the two techniques; (4) although both the PMTD and MIS-TLIF groups were quantitatively evaluated for pain and function, they did not evaluate outcomes such as satisfaction and quality of life. Therefore, to further verify the conclusions of the study, we conducted a multicenter prospective randomized controlled study (ChiCTR2100047365) to comprehensively assess patients' early and long-term postoperative pain, functional status, quality of life, and other outcome indicators.

CONCLUSION

Compared with MIS TLIF, PMTD in the treatment of patients with DLS-I-LSS showed no statistically significant differences in ODI improvement, VAS score for low back pain improvement, VAS score for leg pain improvement, and adverse event rates at 2 years after surgery; however, there was a shorter duration of hospital stay, shorter operation time, less blood loss, and lower hospitalization costs. BMI, presence or absence of diabetes, and baseline ODI score were the main influencing factors for the improvement of ODI in patients with DLS-I-LSS after minimally invasive surgery. The less extensive and less expensive treatment may be the primary surgical choice for most patients with DLS-I-LSS.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Ethics Committee of Fujian Medical University Union Hospital. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CMC and ZYL developed the concept of the manuscript. ZYL and RW conducted the analysis of the data, then ZYL, XJX, JR, YC composed and edited the manuscript text, figures, and tables. All authors contributed to the article and approved the submitted version.

REFERENCES

1. Kalichman L, Kim DH, Li L, Guermazi A, Berkin V, Hunter DJ. Spondylolysis and spondylolisthesis: prevalence and association with low back pain in the adult community-based population. *Spine (Phila Pa 1976)*. (2009) 34:199–205. doi: 10.1097/BRS.0b013e31818edcfd
2. Bond M, Evaniew N, Bailey CS, Glennie RA, Paquet J, Dea N, et al. Back pain in surgically treated degenerative lumbar spondylolisthesis: what can we tell our patients? *Spine J*. (2020) 20:1940–7. doi: 10.1016/j.spinee.2020.08.009
3. Simmonds AM, Rampersaud YR, Dvorak MF, Dea N, Melnyk AD, Fisher CG. Defining the inherent stability of degenerative spondylolisthesis: a systematic review. *J Neurosurg Spine*. (2015) 23:178–89. doi: 10.3171/2014.11.SPINE1426
4. Bydon M, Alvi MA, Goyal A. Degenerative lumbar spondylolisthesis: definition, natural history, conservative management, and surgical treatment. *Neurosurg Clin N Am*. (2019) 30:299–304. doi: 10.1016/j.nec.2019.02.003
5. Watters 3rd WC, Bono CM, Gilbert TJ, Kreiner DS, Mazanec DJ, Shaffer WO, et al. An evidence-based clinical guideline for the diagnosis and treatment of degenerative lumbar spondylolisthesis. *Spine J*. (2009) 9:609–14. doi: 10.1016/j.spinee.2009.03.016
6. Weinstein JN, Lurie JD, Tosteson TD, Zhao W, Blood EA, Tosteson AN, et al. Surgical compared with nonoperative treatment for lumbar degenerative spondylolisthesis. four-year results in the Spine Patient Outcomes Research Trial (SPORT) randomized and observational cohorts. *J Bone Joint Surg Am*. (2009) 91:1295–304. doi: 10.2106/JBJS.H.00913
7. Kalichman L, Hunter DJ. Diagnosis and conservative management of degenerative lumbar spondylolisthesis. *Eur Spine J*. (2008) 17:327–35. doi: 10.1007/s00586-007-0543-3
8. Pearson AM, Lurie JD, Blood EA, Frymoyer JW, Braeutigam H, An H, et al. Spine patient outcomes research trial: radiographic predictors of clinical outcomes after operative or nonoperative treatment of degenerative spondylolisthesis. *Spine (Phila Pa 1976)*. (2008) 33:2759–66. doi: 10.1097/BRS.0b013e31818e2d8b
9. Dhall SS, Wang MY, Mummaneni PV. Clinical and radiographic comparison of mini-open transforaminal lumbar interbody fusion with open transforaminal lumbar interbody fusion in 42 patients with long-term follow-up. *J Neurosurg Spine*. (2008) 9:560–5. doi: 10.3171/SPI.2008.9.08142
10. Austevoll IM, Gjestad R, Solberg T, Storheim K, Brox JI, Hermansen E, et al. Comparative effectiveness of microdecompression alone vs decompression plus instrumented fusion in lumbar degenerative spondylolisthesis. *JAMA Netw Open*. (2020) 3:e2015015. doi: 10.1001/jamanetworkopen.2020.15015
11. Chan AK, Sharma V, Robinson LC, Mummaneni PV. Summary of guidelines for the treatment of lumbar spondylolisthesis. *Neurosurg Clin N Am*. (2019) 30:353–64. doi: 10.1016/j.nec.2019.02.009
12. Weinstein JN, Lurie JD, Tosteson TD, Hanscom B, Tosteson AN, Blood EA, et al. Surgical versus nonsurgical treatment for lumbar degenerative spondylolisthesis. *N Engl J Med*. (2007) 356:2257–70. doi: 10.1056/NEJMoa070302
13. Försth P, Ólafsson G, Carlsson T, Frost A, Borgström F, Fritzell P, et al. Controlled trial of fusion surgery for lumbar spinal stenosis. *N Engl J Med*. (2016) 374:1413–23. doi: 10.1056/NEJMoa1513721
14. Ghogawala Z, Dziura J, Butler WE, Dai F, Terrin N, Magge SN, et al. Laminectomy plus fusion versus laminectomy alone for lumbar spondylolisthesis. *N Engl J Med*. (2016) 374:1424–34. doi: 10.1056/NEJMoa1508788
15. Bae HW, Rajaee SS, Kanim LE. Nationwide trends in the surgical management of lumbar spinal stenosis. *Spine (Phila Pa 1976)*. (2013) 38:916–26. doi: 10.1097/BRS.0b013e3182833e7c
16. Foley KT, Smith MM, Rampersaud YR. Microendoscopic approach to far-lateral lumbar disc herniation. *Neurosurg Focus*. (1999) 7(5):e5. doi: 10.3171/foc.1999.7.6.6
17. Greiner-Perth R, Böhm H, El Saghir H. Microscopically assisted percutaneous nucleotomy, an alternative minimally invasive procedure for the operative treatment of lumbar disc herniation: preliminary results. *Neurosurg Rev*. (2002) 25:225–7. doi: 10.1007/s10143-002-0220-2
18. Chunmei C, Yuandong Z, Chaofeng F, Wei Z, Rui W, Feng L, et al. Unilateral approach for microchannel percutaneous bilateral decompression of lumbar spinal stenosis. *Chin J Neurosurg*. (2016) 32:1208–13. doi: 10.3760/cma.j.issn.1001-2346.2016.12.005
19. Chunmei C, Xinguang Y, Shuo W. Tubular access spine surgery: a new concept of minimal invasive spine surgery. *Zhonghua yi xue za zhi*. (2020) 100:244–6. doi: 10.3760/cma.j.issn.0376-2491.2020.04.002

20. Mobbs RJ, Li J, Sivabalan P, Raley D, Rao PJ. Outcomes after decompressive laminectomy for lumbar spinal stenosis: comparison between minimally invasive unilateral laminectomy for bilateral decompression and open laminectomy: clinical article. *J Neurosurg Spine*. (2014) 21:179–86. doi: 10.3171/2014.4.SPINE13420
21. Serban D, Calina N, Tender G. Standard versus minimally invasive transforaminal lumbar interbody fusion: a prospective randomized study. *BioMed Res Int*. (2017) 2017:7236970. doi: 10.1155/2017/7236970
22. de Kunder SL, van Kuijk SMJ, Rijkers K, Caelers I, van Hemert WLW, de Bie RA, et al. Transforaminal lumbar interbody fusion (TLIF) versus posterior lumbar interbody fusion (PLIF) in lumbar spondylolisthesis: a systematic review and meta-analysis. *Spine J*. (2017) 17:1712–21. doi: 10.1016/j.spinee.2017.06.018
23. Mobbs RJ, Phan K, Malham G, Seex K, Rao PJ. Lumbar interbody fusion: techniques, indications and comparison of interbody fusion options including PLIF, TLIF, MI-TLIF, OLIF/ATP, LLIF and ALIF. *J Spine Surg*. (2015) 1:2–18. doi: 10.3978/j.issn.2414-469X.2015.10.05
24. Pelton MA, Phillips FM, Singh K. A comparison of perioperative costs and outcomes in patients with and without workers' compensation claims treated with minimally invasive or open transforaminal lumbar interbody fusion. *Spine (Phila Pa 1976)*. (2012) 37:1914–9. doi: 10.1097/BRS.0b013e318257d490
25. Parajón A, Alimi M, Navarro-Ramirez R, Christos P, Torres-Campa JM, Moriguchi Y, et al. Minimally invasive transforaminal lumbar interbody fusion: meta-analysis of the fusion rates. What is the optimal graft material? *Neurosurgery*. (2017) 81:958–71. doi: 10.1093/neuros/nyx141
26. Virk SS, Yu E. The Top 50 Articles on minimally invasive spine surgery. *Spine*. (Phila Pa 2017) 42:513–9. doi: 10.1097/BRS.0000000000001797
27. Park Y, Ha JW, Lee YT, Sung NY. Minimally invasive transforaminal lumbar interbody fusion for spondylolisthesis and degenerative spondylosis: 5-year results. *Clin Orthop Relat Res*. (2014) 472:1813–23. doi: 10.1007/s11999-013-3241-y
28. Seng C, Siddiqui MA, Wong KP, Zhang K, Yeo W, Tan SB, et al. Five-year outcomes of minimally invasive versus open transforaminal lumbar interbody fusion: a matched-pair comparison study. *Spine (Phila Pa 1976)*. (2013) 38:2049–55. doi: 10.1097/BRS.0b013e3182a8212d
29. Chan AK, Bisson EF, Bydon M, Glassman SD, Foley KT, Potts EA, et al. A comparison of minimally invasive transforaminal lumbar interbody fusion and decompression alone for degenerative lumbar spondylolisthesis. *Neurosurg Focus*. (2019) 46:E13. doi: 10.3171/2019.2.FOCUS18722
30. Lener S, Wipplinger C, Hernandez RN, Hussain I, Kirnaz S, Navarro-Ramirez R, et al. Defining the MIS-TLIF: a systematic review of techniques and technologies used by surgeons worldwide. *Glob spine J*. (2020) 10:151s–67s. doi: 10.1177/2192568219882346
31. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP. Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *BMJ*. (2007) 335:806–8. doi: 10.1136/bmj.39335.541782.AD
32. Niggemann P, Kuchta J, Grosskurth D, Beyer HK, Hoeffer J, Delank KS. Spondylolysis and isthmic spondylolisthesis: impact of vertebral hypoplasia on the use of the Meyerding classification. *Br J Radiol*. (2012) 85:358–62. doi: 10.1259/bjr/60355971
33. Street JT, Andrew Glennie R, Dea N, DiPaola C, Wang Z, Boyd M, et al. A comparison of the Wiltse versus midline approaches in degenerative conditions of the lumbar spine. *J Neurosurg Spine*. (2016) 25:332–8. doi: 10.3171/2016.2.SPINE151018
34. Mannion AF, Bianchi G, Mariaux F, Fekete TF, Reitmeir R, Moser B, et al. Can the charlson comorbidity index be used to predict the ASA grade in patients undergoing spine surgery? *Eur Spine J*. (2020) 29:2941–52. doi: 10.1007/s00586-020-06595-1
35. Fritz JM, Irrgang JJ. A comparison of a modified Oswestry Low Back Pain Disability Questionnaire and the Quebec Back Pain Disability Scale. *Phys Ther*. (2001) 81:776–88. doi: 10.1093/ptj/81.2.776
36. Ferreira-Valente MA, Pais-Ribeiro JL, Jensen MP. Validity of four pain intensity rating scales. *Pain*. (2011) 152:2399–404. doi: 10.1016/j.pain.2011.07.005
37. Schroeder GD, Kepler CK, Kurd MF, Vaccaro AR, Hsu WK, Patel AA, et al. Rationale for the surgical treatment of lumbar degenerative spondylolisthesis. *Spine (Phila Pa 1976)*. (2015) 40:E1161–6. doi: 10.1097/BRS.0000000000001116
38. Herkowitz HN, Kurz LT. Degenerative lumbar spondylolisthesis with spinal stenosis. A prospective study comparing decompression with decompression and intertransverse process arthrodesis. *J Bone Joint Surg Am*. (1991) 73:802–8. doi: 10.2106/00004623-199173060-00002
39. Guigui P, Ferrero E. Surgical treatment of degenerative spondylolisthesis. *Orthop Traumatol Surg Res*. (2017) 103:S11–S20. doi: 10.1016/j.otsr.2016.06.022
40. Martin BI, Mirza SK, Comstock BA, Gray DT, Kreuter W, Deyo RA. Reoperation rates following lumbar spine surgery and the influence of spinal fusion procedures. *Spine (Phila Pa 1976)*. (2007) 32:382–7. doi: 10.1097/01.brs.0000254104.55716.46
41. Clark AJ, Safaee MM, Khan NR, Brown MT, Foley KT. Tubular microdiscectomy: techniques, complication avoidance, and review of the literature. *Neurosurg Focus*. (2017) 43:E7. doi: 10.3171/2017.5.FOCUS17202
42. Hubbe U, Franco-Jimenez P, Klingler JH, Vasilikos I, Scholz C, Kogias E. Minimally invasive tubular microdiscectomy for recurrent lumbar disc herniation. *J Neurosurg Spine*. (2016) 24:48–53. doi: 10.3171/2015.4.SPINE14883
43. Liang HF, Liu SH, Chen ZX, Fei QM. Decompression plus fusion versus decompression alone for degenerative lumbar spondylolisthesis: a systematic review and meta-analysis. *Eur Spine J*. (2017) 26:3084–95. doi: 10.1007/s00586-017-5200-x
44. Kreines K, Johnson E, Albrink M, Knatterud GL, Levin ME, Lewitan A, et al. The course of peripheral vascular disease in non-insulin-dependent diabetes. *Diabetes Care*. (1985) 8:235–43. doi: 10.2337/diacare.8.3.235
45. Selvarajah D, Kar D, Khunti K, Davies MJ, Scott AR, Walker J, et al. Diabetic peripheral neuropathy: advances in diagnosis and strategies for screening and early intervention. *Lancet Diabetes Endocrinol*. (2019) 7:938–48. doi: 10.1016/S2213-8587(19)30081-6
46. Vinik AI, Nevoret ML, Casellini C, Parson H. Diabetic neuropathy. *Endocrinol Metab Clin North Am*. (2013) 42:747–87. doi: 10.1016/j.ecl.2013.06.001
47. Rihn JA, Kurd M, Hilibrand AS, Lurie J, Zhao W, Albert T, et al. The influence of obesity on the outcome of treatment of lumbar disc herniation: analysis of the Spine Patient Outcomes Research Trial (SPORT). *J Bone Joint Surg Am*. (2013) 95:1–8. doi: 10.2106/JBJS.K.01558
48. Brodke DS, Goz V, Voss MW, Lawrence BD, Spiker WR, Hung M. PROMIS PF CAT outperforms the ODI and SF-36 physical function domain in spine patients. *Spine (Phila Pa 1976)*. (2017) 42:921–9. doi: 10.1097/BRS.0000000000001965
49. Wang M, Luo XJ, Ye YJ, Zhang Z. Does concomitant degenerative spondylolisthesis influence the outcome of decompression alone in degenerative lumbar spinal stenosis? A meta-analysis of comparative studies. *World Neurosurg*. (2019) 123:226–38. doi: 10.1016/j.wneu.2018.11.246
50. Chang W, Yuwen P, Zhu Y, Wei N, Feng C, Zhang Y, et al. Effectiveness of decompression alone versus decompression plus fusion for lumbar spinal stenosis: a systematic review and meta-analysis. *Arch Orthop Trauma Surg*. (2017) 137:637–50. doi: 10.1007/s00402-017-2685-z
51. Yavin D, Casha S, Wiebe S, Feasby TE, Clark C, Isaacs A, et al. Lumbar fusion for degenerative disease: a systematic review and meta-analysis. *Neurosurgery*. (2017) 80:701–15. doi: 10.1093/neuros/nyw162

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SYSTEMATIC REVIEW
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Critical Review of the State-of-the-Art on Lumbar Percutaneous Cement Discoplasty

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Interbody fusion is the gold standard surgery to treat lumbar disc degeneration disease but can be a high-risk procedure in elderly and polymorbid patients. Percutaneous Cement Discoplasty (PCD) is a minimally invasive technique developed to treat advanced stage of disc degeneration exhibiting a vacuum phenomenon. A patient-specific stand-alone spacer is created by filling the disc with polymethylmethacrylate cement, allowing to recover the disc height and improve the patient's conditions. As it has recently been introduced in the lumbar spine, this review aims to present a transversal state-of-the-art of the surgery from its clinical practice and outcome to biomechanical and engineering topics. The literature was searched across multiple databases using predefined keywords over no limited period of time. Papers about vertebroplasty were excluded. Among 466 identified papers, the relevant ones included twelve clinical papers reporting the variations of the surgical technique, follow-up and complications, four papers reporting biomechanical *ex vivo* and numerical tests, and four letters related to published clinical papers. Papers presenting the operative practice are reported, as well as follow-ups up to four years. The papers found, consistently reported that PCD significantly improved the clinical status of the patients and maintained it after two years. Spine alignment was impacted by PCD: the sacral slope was significantly reduced, and disc height increased. The foramen opening correlated to the volume of injected cement. Substitutes to the acrylic cement exhibited better osteointegration and mechanical properties closer to bone tissue. Finally, limitations and risks of the surgery are discussed as well as potential improvements such as the development of new filling materials with better mechanical properties and biological integration or the investigation of the inner disc.

Keywords: percutaneous cement discoplasty, minimally invasive spinal surgery, spine biomechanics, clinical outcome, systematic review

Abbreviations: BME, bone marrow edema; DIC, digital image correlation; IVD, intervertebral disc; LA, linoleic acid; MC, mineralized collagen; ODI, Oswestry disability index; PCD, percutaneous cement discoplasty; PDCP, percutaneous disc cementoplasty; PIPI, percutaneous intervertebral-vacuum polymethylmethacrylate injection; PMMA, polymethylmethacrylate; SD, standard deviation; VAS, visual analogue scale; VP, vacuum phenomenon.

INTRODUCTION

The ageing of the global population due to the increase of life expectancy directly increases the prevalence of spine disease and in particular degeneration of the lumbar Intervertebral Disc (IVD) (1). With time, the IVD water content decreases leading to tissue breakdown and to loss of disc height (2). Consequently, the foramen space between adjacent lumbar vertebrae is reduced, creating neural stenosis and inducing low back pain in some cases (3). In the most extreme degrees of disc degeneration, the nucleus is replaced by a vacuum phenomenon (VP), creating a large instability of the spine segment and extreme compression of the nerves (4).

Lumbar IVD degeneration treatments range from physiological exercises to surgical procedure. Depending on the stage of the disease, the invasiveness level of the treatment strategy varies. At an early stage, conservative management is prioritized. In this case, restorative, reconstructive or disc replacement strategies are applied: a review on this topic has recently been published (5). The most common surgical solution, with the longest follow up is interbody fusion, requiring insertion of a cage and bone graft combined to posterior fixations to restore the intervertebral height and stabilize the spine. Pain-relieving injections and molecular treatments such as cell, growth factor, and gene therapies (6) have been developed to handle early stages of the degenerative process. Reconstructive strategies include percutaneous techniques for decompression and biomaterial implantation (7). Finally, for advanced degeneration, total disc arthroplasty and particularly rigid fusion are favoured (8). This late surgical technique is a long surgical procedure requiring a general anaesthesia and a long recovery. It is also associated with high risks of bleeding and complications. Therefore, it can be contraindicated for elderly and polymorbid patients. For those unsuitable patients, the absence of efficient treatment led to the development of minimally invasive technique called Percutaneous Cement Discoplasty (PCD) (9).

PCD is dedicated to treat patients with advanced disc degeneration exhibiting a VP. The procedure consists in the injection of an acrylic cement within the disc to fully fill the cavity. The cement mass then acts as a stand-alone implant, restoring the disc height.

Historically, a similar technique has been implemented in the cervical spine as an alternative to interbody fusion cages for spine segment stabilization. Injection of bone cement in the disc was introduced in the Eighties by Roosen (10). The technique was then replicated *in vivo* (11, 12) and *in vitro* (13–15) to investigate the surgical outcome and biomechanical consequences of such a treatment on the cervical spine in comparison to spacer. It was found that acrylic cement stabilized the spine similarly to other cages (11, 12, 15), but showed a lower subsidence in adjacent vertebrae (13, 14).

Thus, PCD is considered as a promising technique for spinal repair. However, the knowledge around the surgery and its consequences on the lumbar spine is still under investigation. Papers have been recently published on several aspects of PCD, from clinical cohort papers to engineering papers on biomechanics and biomaterials.

This review aims to present the various research areas related to PCD to provide a clear view of the progresses and needs in this field. The review aimed to assess of the efficiency of this technique in terms of clinical outcome for the patient, but also in terms of objective parameters such as spinal behaviour and spine stability.

METHODS

Search Strategy

This review includes papers of all types from articles to letters to the editor in peer-reviewed journals. No single study design was specified since the review aimed to collect all PCD-related publications. No time frame was defined although first publications mentioning PCD were published in 1982 and reporting lumbar PCD in 2015. Only peer-reviewed publications with an English version were considered.

The review established a state-of-the-art about PCD. Therefore, the inclusion criteria rather targeted the qualificatives of PCD to ensure both quantitative and qualitative papers to be retrieved. The review focused on surgical practices applied on the intervertebral discs of the thoracolumbar spine and consisting of injecting acrylic bone cement within a disc presenting a vacuum phenomenon. Papers about vertebroplasty were excluded as well as surgeries which fixed the spinal posterior elements.

The search was performed on the electronic databases PubMed and Scopus. Additionally, the references of the screened papers were reviewed to search potential related studies (**Figure 1**).

The papers collected from the databases were checked for duplicates. A first screening was based on the titles and abstracts of the papers, to ensure that the papers indeed focused on the intended topic and was not picked erroneously. The final eligibility of the papers was based on the full text content to fully assess all criteria. This process was initially performed by one author, but the results were approved by the others. Among the eligible papers, separation was performed between qualitative papers assessing the characteristics of the surgery and its consequences, and papers including quantitative evaluation of PCD outcome.

Data Collection Process

Qualitative and quantitative data were then extracted from the papers using a form established by the authors to assess the quality of the papers and their content. The variables sought in all papers were:

- Type of the study (cohort/retrospective/prospective/*in vitro*/numerical)
- Presence and clarity of the inclusion criteria of specimens/patients in the study
- Presence and clarity of the exclusion criteria of specimens/patients from the study
- Presence of comparison between groups of persons/patients undergoing two different treatments

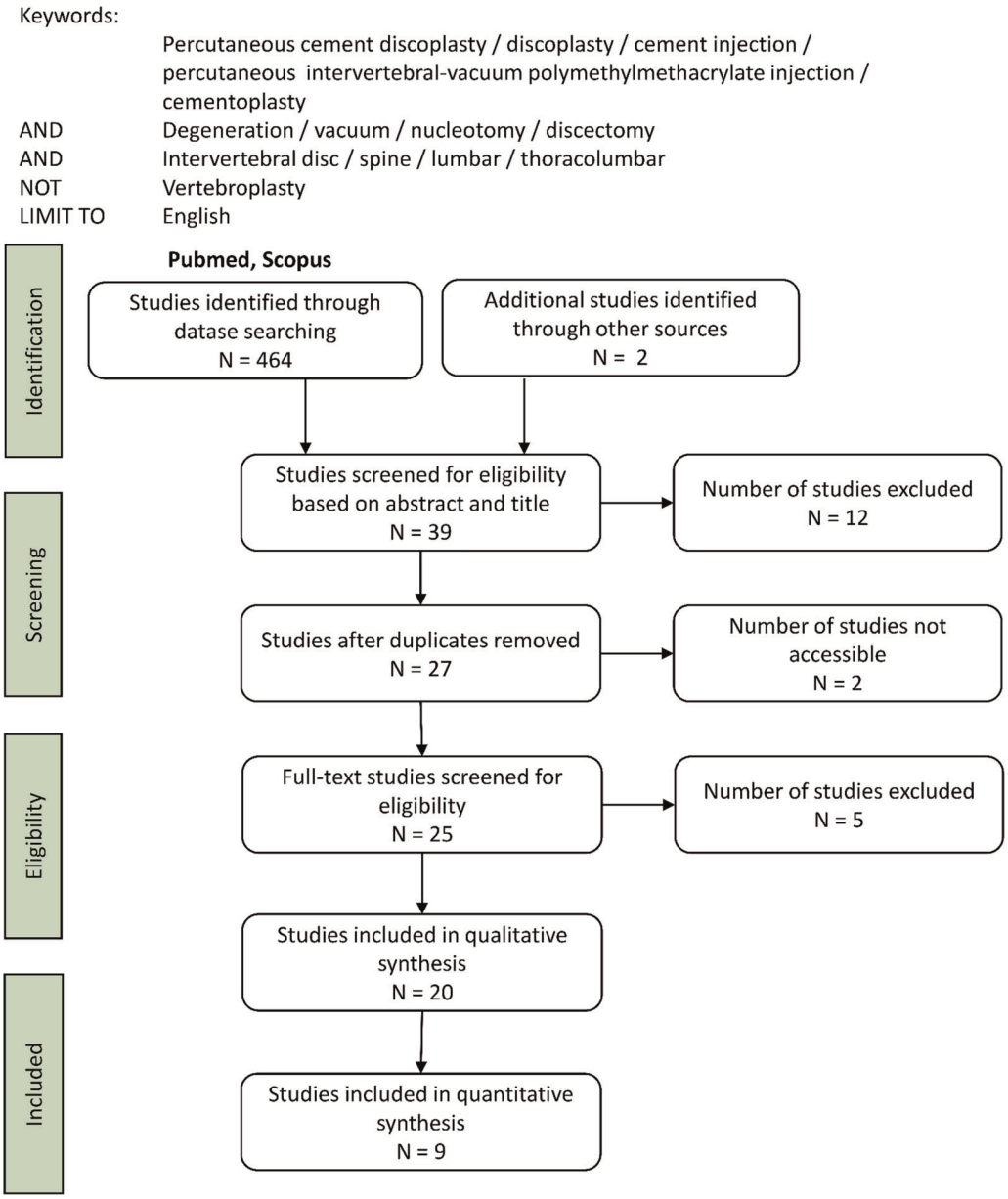

FIGURE 1 | Workflow of the search strategy.

As the review covered various types of papers from clinical to biomechanical papers, additional variables were investigated, most being suitable for the majority of the papers:

- Presence and duration of a follow-up
- Period of the study
- Number of persons in the cohort/specimens
- Inclusion/exclusion criteria for the persons/specimens
- Variables observed and corresponding parameters measured
- Frequency of measurement
- Nature of the parameters' outcome (index, scale, cases)
- Presentation of the operative technique
- Monitoring of the surgery
- Surgical approach chosen
- Use of preliminary medium to assess the volume of cement to inject
- Volume of cement injected
- Duration of the surgery
- Discharge of the patients
- Post-operative treatment/recommendation
- Presence of case presentation
- Complications/limitations

In particular, the review investigated patient outcomes, the operative technique, and potential risks induced by PCD on the spine depending on the type of article collected. For that, a particular interest was brought to:

- Patient self-reported pain, mobility, etc.
- Patient mobility assessed objectively
- Spinal alignment
- Mechanical behaviour of spine
- Disc height/foramen size changes
- Complications/risks

Risk of bias was also verified both at the study level (related to funding for instance) and at the outcome levels. Among the practices recommended to decrease the risk of bias, one can mention the use of an independent observer or a double-blind, the repeatability of measurements, the reproducibility of the measurements by two operators. Conversely, self-reporting of the patient pain would represent subjective results although it is a crucial tool in clinics. This review did not aim to hierarchize some results over others, but to make the reader aware of potential weaknesses and limitations of the available data. Each field of research has its own tools which fill the field needs and complete each other.

Qualitative data were reported, gathering into groups the papers presenting similar values. For quantitative parameters, the mean values reported in each paper were compared using the same scale. To quantify patient's quality of life and pain, Oswestry Disability Index (ODI) and Visual Analogue Scale (VAS) scores are reported using the standard scale from 0 to 100. Spine alignment and stability will be quantified by anatomical parameters in terms of angles and distances.

RESULTS

Results of the Literature Search Process

The search on PubMed and Scopus with the keywords stated above (**Figure 1**) resulted in respectively 32 and 432 papers of all types. In addition, a study conducted by our group and currently in submission was included to the published papers. Reviewing the references of these papers, one more publication was included in the panel. The first screening of the abstracts and titles provided 27 eligible papers. The full-text reading established that 20 publications were qualified for this review on PCD, all written after 2015. Among them, 15 were identified as journal articles covering both clinical and biomechanical investigations, and 5 as letters to the editors commenting some published articles.

The articles found included four prospective studies (9, 16–18), one case study (19), two diagnostic studies (20, 21), five retrospective studies (22–26), four biomechanical studies whose only three published (27–29). The four remaining publications were correspondence to the Editor articulated around two distinct conversations. Following the case study presented by Sola et al., a first letter to the editor was written by Wang et al. to require more details about the operative technique and the outcome (30). The content of the answers from Camino-Willhuber and Sola was published in another letter (31). Additionally, Lazary commented on Sola et al.'s case study, questioning the need of intraoperative neurophysiological monitoring (32). Camino-Willhuber et al. explained their use of the technique with regards to their own surgical experience (33).

Except for the case study, the diagnostic studies, and the letters, all papers provided quantitative data tackling the patient outcome and/or biomechanical parameters. All papers acknowledged their risks of bias and tried to mitigate them.

One must note that the term Percutaneous Cement Discoplasty was not universally used in the literature. Yamada et al. reported the surgical technique in their two papers under the name percutaneous intervertebral-vacuum polymethylmethacrylate injection (PIPI) while Tian et al. used the term percutaneous disc cementoplasty (PDCP). In this review, the surgical technique is named after the most common term: percutaneous cement discoplasty (PCD, $n = 16$ hits in total) rather than PIPI ($n = 2$ hits) or PDCP ($n = 2$ hits).

Among the recorded 20 publications, eight papers included a follow-up involving the recruitment of human participants. Yamada et al. compared groups undergoing PCD to other treatments, whereas the others focused on a preop/postop comparison. For *in vivo* papers, the selection process of the participants was explicitly detailed in the text at minimum, with additional scheme to summarize in Yamada et al. and Kiss et al. papers.

This review gathers all publications linked to PCD, whether they covered the patient outcome or the operative technique. Data collected *in vivo* and *in vitro* are presented separately below. A summary table of the literature results is available in a Figshare file (https://doi.org/10.6084/m9.figshare.19375604).

Operative Technique

Chronological Presentation of PCD Technique

Sixteen publications tackled PCD applied to patients, from the surgical planning to the operative technique itself, and covering the patient outcome. Historically, cement injection in the IVD was primarily introduced to stabilize the cervical spine (10, 15). In 2015, Varga et al. presented the operative technique applied for the first time to the lumbar spine (9), followed in 2018 by Sola et al. (19). Two papers presented case studies (9, 19). Camino-Willhuber et al. focused on the development of a methodology to fine-tune the diagnosis of cases requiring PCD as a treatment (20). Eltes et al. developed a methodology to quantitatively evaluate the impact of the surgery on patient anatomy using medical imaging (21). Finally, ten papers included a follow-up of the patients (9, 16–18, 21–26). While Kiss et al. and Varga et al. (9, 16) investigated PCD as treatment of disc degeneration to restore vertical stability, Yamada et al. applied PCD to specifically treat scoliosis resulting from disc degeneration (17, 18). The paper compared the clinical outcomes of two groups: patients treated with PCD, and patients treated with physiotherapy. Camino-Willhuber et al. addressed the matter by comparing the treatment outcome in patients with and without degenerative scoliosis (22). Another paper by Camino-Willhuber et al. compared the PCD outcome between three

groups of patients depending on their previous spine surgical history at the treated level (24). Finally, Tian et al. reported using PCD after percutaneous lumbar discectomy to treat lumbar disc herniation in two papers (25, 26). One must note that these papers differ in terms of indications of PCD: contrary to the original paper recommendation (9), PCD aimed there to treat a spinal condition unrelated to disc degeneration disease.

Surgical Planning

All authors except Tian et al. defined the same indications for surgery as introduced by Varga et al. As a minimally invasive surgery, PCD is mainly intended to treat patients not suitable for an open surgery. Eligible patients suffer from a Disc Degeneration Disease in an advanced stage (Pfirrmann's grade V) resulting into a VP due to the disappearance of nucleus pulposus. Evidence of foraminal stenosis directly inducing back pain is also an indication, and specifically when pain increases with standing activity and is relieved after resting (https://doi.org/10.6084/m9.figshare.19375604).

Pfirrmann's scale evaluates the intervertebral disc degeneration stage; however PCD principally depends on VP and the surrounding tissue state. For this reason, surgery planning was refined to identify patients having the most suitable pathological condition of the disc and the endplates (20). A new classification of VP, established from Computed Tomography scans, identified four levels of VP based on the rate intervertebral vacuum/disc tissue and two sub-levels depending on the presence of subchondral stenosis. Camino-Willhuber et al. suggested that PCD should be only recommended for partial or complete VP, to reduce the risks of disc protrusions during acrylic cement injection. Additionally, the presence of subchondral stenosis would limit risks of adjacent fractures, in particular in osteoporotic patients.

Some contraindications were presented by Sola (19):

- Severe osteoporosis could jeopardize the integrity of the vertebral bodies after the surgery. Following Wang's letter to the editor (30), Camino-Willhuber and Sola specified that no direct measure of lumbar osteoporosis was used as a threshold to discriminate patients suitable for PCD (31). However, patients with a T-score lower than −2.5 at the hip, or history of bone fracture were referred to endocrinologist for anti-osteoporosis treatment. In their papers, Yamada et al. defined a bone density threshold of 70% of the young adult mean measured by dual-energy x-ray absorptiometry, under which the surgery was not recommended.
- Severe deformity of the spine would exclude patients from receiving PCD. Indeed, although this surgery demonstrated a stabilizing effect on the spine in case of degenerative scoliosis, PCD does not aim to correct severe deformities (31).
- Evidence of tumours, metastases, or infections at the corresponding spine levels.
- Obesity is a limiting factor because it reduces the quality of the fluoroscopy monitoring required during the surgery

Tian et al. presented a different use of PCD (25, 26). In their papers, the combination of percutaneous discectomy and PCD was studied as a treatment to lumbar herniation with endplate osteochondritis. Because percutaneous discectomy alone cannot treat the late condition, PCD was performed as a second step of the surgical treatment. Hence, the recruitment of patients in these studies differed from the criteria above. Eligible patients demonstrated neurological signs related to disc migration with endplate osteochondritis, contained disc protrusion with Modic type I changes of the endplate bone marrow, had no history of surgery at the disc level, and were above 60 years old. Patients were also included after at least 6 weeks of unsuccessful conservative treatment. Similarly, patients were excluded in case of spinal nervous canal stenosis (grades 2 and 3 of Lee et al. (34) and Bartynski and Lin (35) classifications), sequestered disc below or above the centre of the pedicle of the lower vertebral body, calcification of longitudinal ligaments, comorbidities such as cardiovascular disease, diabetes, infection, spinal tumour, or fracture, untreatable coagulopathy, and allergy to polymethyl methacrylate (PMMA).

Surgical Procedure

PCD is a minimally invasive surgery; its operative technique is described by two papers. A radiopaque bone cement was injected to fill the vacuum using an extra-pedicular approach through the Kambin's triangle (9, 16, 32). Yamada et al. prioritized a transpedicular approach for the injection, while Sola et al. also recommended an entrance parallel to the superior lateral pedicle edge except for L5-sacrum level (33). Tian et al. favoured a posterolateral puncture of the disc. Wang et al. confronted the difference of approaches used by Varga and Sola et al., questioning the key factor allowing a homogeneous cement distribution and avoiding leakages (30). Camino-Willhuber and Sola recommended inserting the cannula between middle and anterior third of intervertebral. Stopping injection when bone cement reaches the posterior vertebral wall would prevent leakages (31). If Varga et al. recommended local anaesthesia, what did Tian et al., PCD can be conducted under general anaesthesia as reported by Camino-Willhuber, Kiss and Yamada et al. (16–18, 22, 24). For all papers, the volume of injected cement varied between 3–10 mL depending on the patient and spine level, since cement must entirely fill the vacuum. Because the vacuum was artificially created by percutaneous discectomy, cement volume reported by Tian et al. was slightly inferior (25, 26). The surgery was always performed under fluoroscopic monitoring for a better guidance of the injection and to prevent cement leakage in the neural canals. In addition, Sola et al. recommended the systematic use of intraoperative neurophysiological monitoring during the whole surgery. Lazary argued that risk of nerve root injuries is minimal as long as the surgical rules is followed, and fluoroscopy guidance used (32). Considering the increased cost and duration of PCD procedure caused by neuro-monitoring, its systematic use would not be encouraged. Besides, in the experience of Lazary's group, none of the treated patients suffered from nerve root injuries. Camino-Willhuber explained that neuro-monitoring is specially recommended for the Kambin's triangle approach

which presents more risks of nerve root injuries, in particular in case of deformity (33). Neuro-monitoring, installed during anaesthesia induction, allowed to prevent radicular irritation by changing the cannula entry point in their practice without increasing surgical length. A study on the utility of intraoperative neurophysiological monitoring during PCD reported a sensitivity of 82% and specificity of 99% (23). Before cement injection was introduced, one paper used a medium injected in the disc to assess the volume of required cement (17). The surgery duration varied between papers, depending on the number of treated levels, from about 25 min for one level PCD to more than 1 h for five level PCD. Camino-Willhuber et al. demonstrated that PCD associated with decompression surgery in cases with spinal stenosis, also provided promising outcome to treat the patients (24). Decompression surgery could also be directly indicated from the results of the intraoperative neurophysiological monitoring in case of leakage (33).

Complications and Postoperative Recommendations

Kiss et al. and Yamada et al. reported cement leakages in 4% of the surgeries (respectively 3/63 patients and 3/80) which were treated by decompression surgery (16, 18). In the first paper, all leakages, located in the foramens, caused severe leg pain, and were treated by foraminal decompression during a revision surgery. In the second paper, one leakage was localized in the intervertebral foramen and induced a radicular pain which was treated with anti-inflammatory analgesics. In their papers, Tian et al. reported 1/7 and 2/16 leakages inducing slight pain but the symptoms disappeared within 24 h without treatment (25, 26). Because of the reduced capacity of the disc after PCD to homogeneously transmit the vertical stress at the endplate levels, Wang et al. shared concerns about the increase of fracture risk (30). In their answer, Camino-Willhuber and Sola reported one fracture over 131 treated discs. They explained that fractures were prevented by the degeneration of the endplates which resulted in subchondral sclerosis. No endplate fracture nor cement dislodgement was reported by Yamada et al. (17). One deep infection and one fracture of the adjacent vertebral body were later reported by Camino-Willhuber et al. along with two cases of leakage in the foramen, one disc extrusion and one unexplained pain (22). Overall, in their last paper complications were reported to affect 16% patients, with only 5.7% (9/156) requiring a second operation (24). Cement leakage accounted for 3.2% and vertebral fracture for only 0.6%.

Patients were usually discharged within 3 days, and were encouraged to stand and walk as soon as possible (22). When PCD was associated with lumbar discectomy to treat herniation, the hospitalization lasted about 7 days (25, 26). In the case of the treatment of lumbar degenerative scoliosis, a brace was worn by patients for two months (17). Camino-Willhuber's group did not recommend a brace postoperatively, since patients undergoing PCD did not have risky activities. The only recommendation was to avoid excessive flexion/extension movements and avoid lifting more than 10 kg (31).

Clinical outcome

Among the nine papers including a follow-up, the shortest follow-ups lasted six months (9, 16). Camino-Willhuber et al. presented a 12 months follow-up (22) and a second study of 24 months follow-up (24). Tian et al. presented a 12 months follow-up (25) and a second study with an averaged follow-up of 39 months (26). Yamada et al. first paper measured patient outcome for 24 months (17), the second study based on the same cohort lasted about 63.7 ± 32.4 months (mean ± SD) (18). Periods over which the recruitment and the follow-up of patients was performed widely varied between papers. All details of the follow-ups are summarized in the Figshare file (https://doi.org/10.6084/m9.figshare.19375604).

Selection of Patients

The first patient outcome published paper included 47 participants with complete follow-ups out of 81 initially treated patients (9). 28 participants were included by Kiss et al. in a follow-up of six months (**Figure 2**). The first study of Yamada et al. enrolled 162 participants (17), but was extended in a second paper, resulting in a shorter cohort of 80 participants with a complete follow-up >24 months (18). Tian et al. presented a first study gathering seven patients and a second publication with a 16 patients cohort (25, 26). Camino-Willhuber et al. presented a retrospective study on 54 participants separated into two groups: 37 participants had a degenerative scoliosis, and 17 participants did not present any sign of scoliosis (22). In a second paper, they gathered data of 156 patients from two centres that were separated into three groups based on their previous surgical history (PCD only/PCD after previous lumbar surgery/PCD + decompression) (24).

Among the patients treated by PCD in each paper, the follow-up final participants were filtrated using exclusion criteria similar for most papers. The main exclusion criteria were:

- The absence of complete datasets (16, 22)
- The simultaneous performance of any type of spine surgery even out of L1–5 (16, 22)
- The presence of any previous surgery at the same anatomical level (17, 18, 22)

Additionally, patients with less than 1 year (22) and 2 years (24) of follow-up were excluded from Camino-Willhuber's papers.

In order to study the impact of PCD on degenerative scoliosis, patients with a Cobb angle exceeding 10°, a VAS score above 50 points were selected, and Bone Marrow Edema visible on endplates were selected by Yamada et al.

VAS/ODI Scores

Low back pain graded by the VAS score was reported over the two years of follow-up (**Figure 3**). In all papers, the postop VAS score was significantly improved compared to preop, and at every step of the follow up. In the two longest studies, the pain level increased again with time, but remained significantly reduced compared to preoperative condition. Papers reported the disability to perform daily activities following ODI variations. Similar to VAS, all papers reported

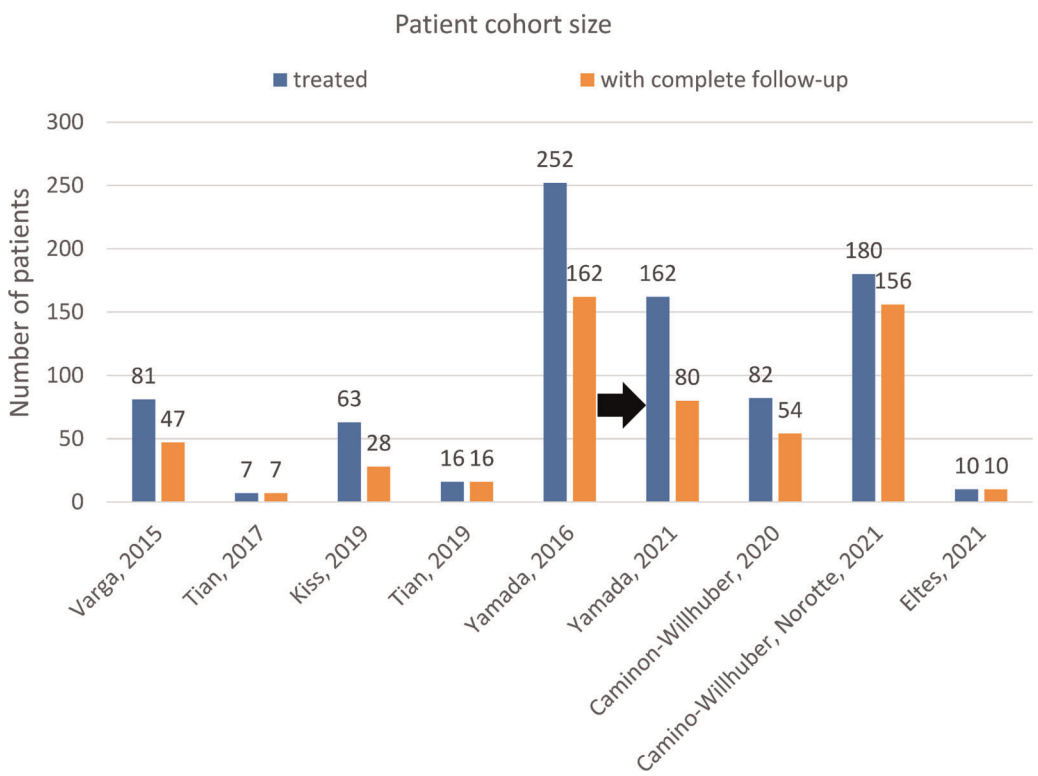

FIGURE 2 | Patient involved in the clinical follow-up studies, from the initial recruitment to the final group. The difference between the number of treated patients and patients finally enrolled in the reported follow-ups was explained by the elimination of patient having an incomplete follow-up, undergoing other spine surgery following PCD, or not matching the inclusion criterion.

a significantly reduced ODI post-surgery compared to preoperative which was still present after two years.

Radiographic Parameters

Bone Marrow Edema (BME) is an accumulation of fluid in the bone marrow which can occur in case of injury or pathological condition and is associated to low back pain. Yamada et al. found a moderate positive correlation between BME and VAS as well as a weak positive correlation with ODI. The BME score decreased after PCD and for the duration of the follow up (>2 years) assessing the recession of the edema in the vertebral bodies (18).

The Cobb's angle was measured by Yamada et al. and Camino-Willhuber et al. preop and followed for 2 years (**Figure 4**). After the intervention, the Cobb's angle was significantly reduced in the scoliotic group ($p = 0.0006$), while the non-scoliotic group did not exhibit any significant change (22). The comparison between patients treated with PCD and physiologic treatments during the follow-up showed the increasing significant effect of the surgical treatment on the Cobb's angle, however the Cobb's angle increased during the follow-up. L1–L5 lumbar lordosis was not significantly impacted by PCD ($p > 0.05$), while the segmental (in the treated and non-treated motion segments) lordosis exhibited a significant increase ($p < 0.05$) (16). Conversely, another paper reported a significant increase of lumbar lordosis at one year postop ($p = 0.0001$) in patient with lumbar scoliosis but no significant changes in segmental lordosis (22).

The pelvic incidence remained unchanged six months after PCD ($p > 0.05$) (16). The sacral slope significantly increased postop in two papers ($p < 0.01$) and the change was maintained at follow-up (16) (**Figure 4**). The correction of sacral slope was positively correlated with the improvement of ODI. The pelvic tilt significantly decreased immediately after the intervention ($p < 0.05$), and the drop remained constant after 6 months (16). Lumbar lordosis was not significantly impacted by PCD ($p > 0.05$), while the segmental lordosis exhibited a significant increase ($p < 0.05$) (16). Conversely, another paper reported a significant recovery of lumbar lordosis at one year postop ($p = 0.0001$) in patients with lumbar scoliosis but no significant changes in segmental lordosis (22).

L1–L5 lumbar scoliosis and segmental scoliosis were significantly reduced in case of single-level PCD (16). The intervention significantly reduced the scoliosis angle postop ($p < 0.05$), and after 6 months no change from postop was observed ($p > 0.05$). The impact of multilevel PCD on scoliosis significantly differed from the single-level surgery: lumbar scoliosis was reduced while segmental scoliosis significantly increased.

In the sagittal plane, anterior and posterior disc height were significantly improved by PCD ($p < 0.001$ for both). The

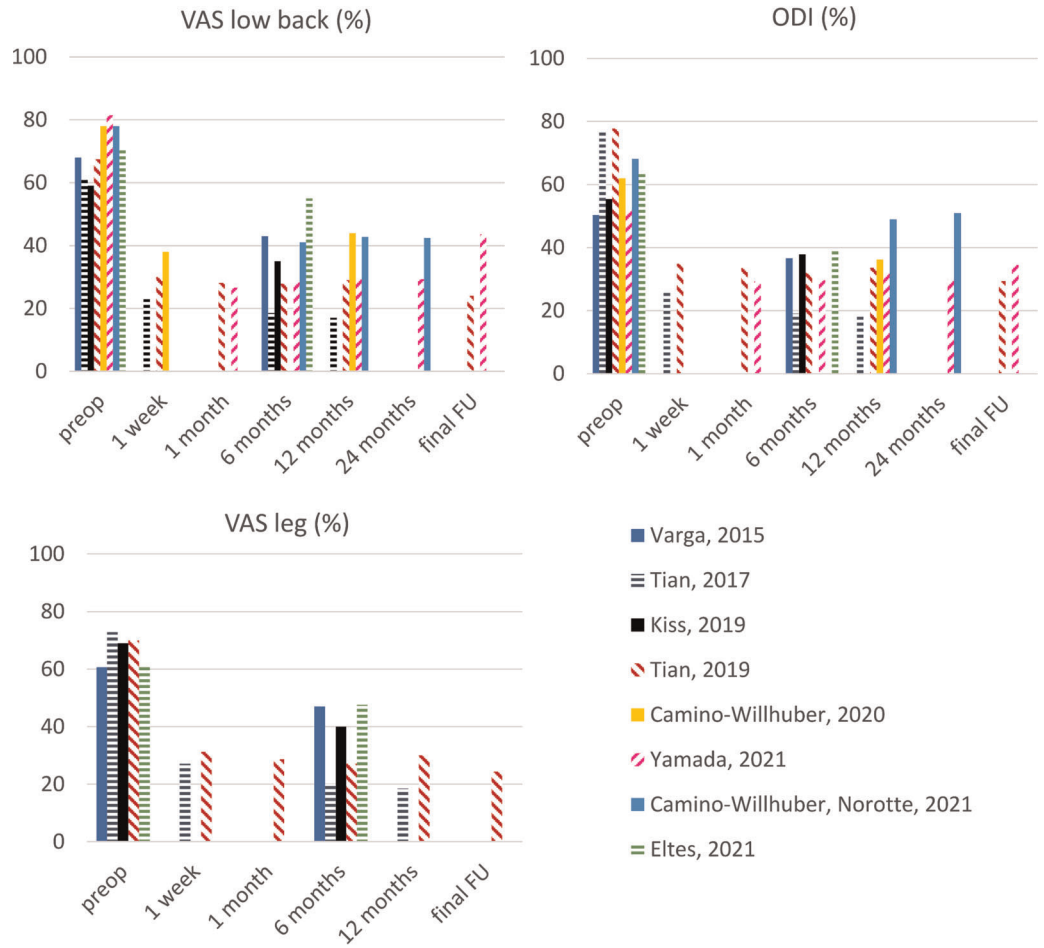

FIGURE 3 | VAS and ODI scores chronologically reported from preoperative to two years postoperative. Fu: follow-up.

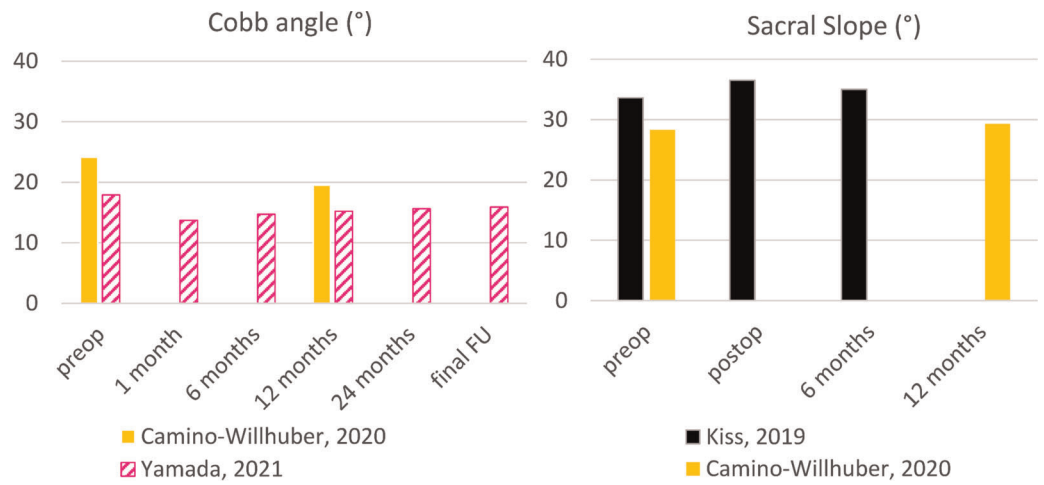

FIGURE 4 | Impact of discoplasty on the sacral slope and Cobb angle.

interpedicular height showed a significant increase after surgery in treated segments ($p < 0.001$) and the change was constant overtime (16).

Biomechanical Assessment of the Effects of Discoplasty

In parallel to patient outcome investigation, *in vitro* and *in silico* studies investigated the biomechanical consequences of PCD. As application of PCD on the low thoracic/lumbar spine is recent, engineering research on the topic is currently limited.

Geometric Changes Associated with PCD

The first interest of the technical papers was to provide objective data to evaluate the success of the surgery to match the clinical expectations. In order to relieve pain, PCD aimed to fill VP with acrylic bone cement in order to increase the disc height and achieve an increase of the foramen space.

Postoperatively, the *in vivo* cement distribution was segmented from CT scans and characterised in terms of volume and surface of the cement mass by Eltes et al. (21). The cement axial thickness between the endplates was also measured for each treated disc. A large variability of volume (3.8–13.1 mL range) and shape was reported, which was induced by the wide variations of musculoskeletal status and degeneration of each patient. Improvement of the patient outcome was correlated to thicker cement mass. In addition, in an *in vitro* study written by our group and currently in submission, discoplasty was reproduced on 27 cadaveric specimens and the volume of injected cement was measured on CT scans images. Supporting Eltes' conclusions, the volume of cement varied widely between specimens (2.0–8.9 mL range) within the same range as *in vivo* measurements.

Techens et al. compared ten porcine lumbar discs *in vitro*, in the intact condition, after nucleotomy, and after simulated PCD tested in flexion and extension. In both motions, the posterior disc height decreased by more than 15% after nucleotomy, whereas discoplasty significantly restored it. In extension, the posterior disc height after surgery did not differ significantly from the intact disc. This *in vitro* investigation confirmed the disc height increase clinically observed (28). The same protocol was applied to 27 cadaveric specimens (Techens et al., submitted) by our group and PCD significantly increased posterior disc height in flexion (41% ± 46%) and extension (35% ± 38%) in comparison to after nucleotomy.

Eltes et al. developed an 3D volumetric method to quantify the preop-postop change of the foramen space from tomographic images. PCD significantly decompressed the foramens despite the wide difference of volumetric changes (mean = 2295 mm^3, SD = 1181, $n = 16$). Foraminal decompression was favoured by higher volume, larger surface and lower surface-volume ratio (21).

Biomechanical Properties of the Spine After Discoplasty

Although PCD does not primarily aim to stabilize the spine, stability is often an additional concern in disc degeneration. Techens et al. measured the *in vitro* range of motion and stiffness following PCD on porcine lumbar segments (28). No significant change was observed despite a decrease of the ROM in flexion and an increase in extension compared to intact discs. Discoplasty recovered the intact ROM compared to nucleotomy. The strains measured after discoplasty on the specimen surface partially regained the distribution observed with intact discs. PCD also reduced the peak strains observed after nucleotomy. Another study under submission investigated the *in vitro* range of motion and stiffness following PCD on human lumbar segments. PCD significantly reduced the ROM and increased the elastic stiffness in flexion only. In addition, the laxity zone was significantly shortened by the surgery in both motions. The strain intensity measured on the specimen disc surface decreased after PCD compared to the distribution in nucleotomy. Besides, in both motions the specimens exhibited lower peak strain values after the surgery, indicating no local extreme tissue deformation.

Alternative Materials for Discoplasty

Research on PCD also covered improvements of the technique to provide a better stabilization of the spine and improvement of patient's condition. Osteogenic mineralized collagen (MC) modified polymethylmethacrylate (PMMA) cement was investigated by Yang et al. as a substitute to acrylic bone cement for PCD. With MC particle size ranging between 300 and 400 micrometers, injectability, hydrophilicity, and mechanical properties of MC-PMMA were characterised (29). After implantation in goat, MC-PMMA showed a significant better osteointegration than standard acrylic cement with a higher ratio between the cement surface in contact with bone and the cement total surface (circumferential contact index). Moreover, MC-PMMA triggered a limited reaction from the immune system, in comparison to standard acrylic cement which exhibited a large fibrous encapsulation. MC-modified PMMA exhibited significantly reduced stiffness (three-points bending elastic modulus of 2.4–2.8 GPa for frequencies of 1–10 Hz), which supposedly would reduce the risks of bone fracture. Thus, MC-PMMA was presented as a promising alternative to pure acrylic bone cement for disc degeneration treatment with PCD. Targeting the same objective of injecting a material which would reduce mechanical stresses on the endplates, Lewin et al. developed an *in silico* model of the spine in order to test low modulus PMMA cements (27). Three modified PMMA-based cements with different concentrations of linoleic acid (LA) were tested *in vitro* to extract mechanical parameters. Elastic modulus of LA-PMMA was up to ten times smaller than the original PMMA-based cement, however the modulus increased over time. The numerical model showed that the stress average increased on the endplates after discoplasty, but the stresses decreased with higher content of LA. This material seems also a promising alternative to acrylic cement for discoplasty although some aspects still require optimization, such as the material mechanical stability over time.

Limitations and Risks of Discoplasty

As PCD is a minimally invasive surgical technique, it reduces the risks of clinical complications compared to the open

surgical treatments of degenerative disc disease. However, it still implies limitations and risks reported by the previous papers. Among the rare permanent complications reported, cement leakage in the intervertebral foramen and vertebral body fracture were the most common (<5% and <1% respectively) (16, 18, 24). Unlike leakage in the adjacent vertebrae which are harmless, cement in the intervertebral foramen could jeopardize the spinal cord integrity. The incidence can be limited by closely monitoring cement injection with fluoroscopy, and using intraoperative neurophysiological monitoring to adapt the approach, entry point and direction chosen for the injection (see 3.2.4).

Vertebral fractures are naturally prevented by endplate sclerosis, and by selecting patients with sufficient bone density. Pre-operative treatments can also be implemented to strengthen the bone structures. Additionally, PCD creates a patient-specific cement spacer adapted to the endplate shape: this increases the contact surface for the transmission of the loads at the cement-endplate interface. Although no dedicated investigation of the intra-discal stress and subsidence after PCD has been conducted so far, an increased bearing surface can be expected to reduce the pression on the endplates compared to other non-specific devices previously used to space the vertebrae (36). Finally, vertebral fractures could be prevented by replacing the injected bone cement with substitute fillers exhibiting reduced mechanical stiffness.

Other concerns can be raised about the interface between the cement and the surrounding annulus. No paper could be found focusing on both the short- and long-term *in vivo* responses of the biological tissue of the disc to the presence of the injected cement. No abnormal inflammatory activity was reported in the follow-ups. Acrylic cement being biocompatible and favouring osteointegration, long-term cemented discs would be expected to fuse and stabilize the treated level. Complications arising from long-term motion such as cement loosening or wear although they have not been studied yet, would therefore seem unlikely. However, substitute filler with better osteointegration would still decrease these risks of complications.

DISCUSSION AND CONCLUSIONS

Disc degeneration disease has a high prevalence, particularly in the elderly, and is responsible for low back pain (1). In the most severe cases, the disappearance of the nucleus pulposus results in the presence of a vacuum which leads the disc to collapse, thus reducing the clearance of the foramens. As polymorbid and old patients are not eligible for an open surgery, they are sometimes treated with a minimally invasive surgery, percutaneous cement discoplasty (9). The aim of this review was to establish a state-of-the-art of the publications related to PCD.

Twenty papers were retrieved through two databases covering clinical and engineering approaches of the surgery. Two papers presented the operative technique and described the criteria for patient selection (9, 19). PCD consists in filling the intradiscal space with injectable acrylic bone cement to replace the VP by a cemented spacer. Patients are usually discharged between one and three days after surgery. PCD is mainly contraindicated in case of severe osteoporosis and severe spine deformity although it stabilized degenerative scoliosis (19). Cement leakage in the vertebral bodies or the foramen are the most common complications but in all reported cases, it had a low prevalence (4% of the treated discs).

Nine papers reported clinical follow-up lasting between 6 months and 4 years for 28–162 patients (9, 16–18, 21, 22, 24–26). All follow-ups concluded that PCD significantly reduced low back pain immediately after surgery and that pain was still relieved at the end of the follow-up. Similarly, the quality of life reported by patient significantly improved post-surgery and the improvement lasted until the end of the study. Patient outcome correlated with the increase of the foramen space following the surgery (21). The disc height was restored by PCD, validating the main objective of surgery. PCD significantly impacted some radiographic parameters, among which the scoliosis angle although the surgery is not primarily recommended to treat scoliosis. Biomechanical studies showed that PCD restored the spine stability during flexion and extension and did not induce irregular deformation of the surface disc tissue (28).

Among the investigations on PCD, two research papers presented variations of bone cement (MC-PMMA and LA-PMMA) as filling material (27, 29). MC-PMMA exhibited a better osteointegration and triggered less the immune system reaction compared to pure acrylic cement, and LA-PMMA reduced the stresses on the endplates reducing risk of bone marrow edema.

The literature reviewed seems to show that PCD is a safe and effective MIS procedure for the treatment of advanced stage disc degeneration in selected cases. However, studies comparing the effectiveness of PCD to conventional treatment options were unavailable. The review showed a major limitation of the clinical studies: only static supine and standing position (loaded by the upper body weight) was investigated. However, axial compression is not the only challenge for disc height and foramen space. The study of potential damaging activities or spine motions was omitted. Questions such as: "Which load could a patient safely carry? Which movement could be safely performed?" were not investigated yet, although patients indicated for PCD were unlikely to carry heavy loads or ostentatiously exercise. Additionally, the spine biomechanical behaviour under various loadings just started to be studied. Thus, a focus on other loading configurations as well as the measurement of different parameters would be needed to complete a rational on the benefits and limitations of percutaneous cement discoplasty.

Directions for possible future research in this area include alternative injectable materials for better biomechanical and clinical performance. Clinical and biomechanical investigations would help optimizing the surgical technique, including point of needle insertion and of cement delivery. Also, one should remember the frame of application of PCD and conduct more investigations in case of change of the indications of the surgery (younger, more active patients, etc.).

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: Figshare folder, DOI: 10.6084/m9.figshare.19375604.

AUTHOR CONTRIBUTIONS

The review was suggested by LC and AL. The literature search and the analysis of the results were performed by CT. The manuscript writing was handled by CT and LC. The manuscript was corrected by AL and PEE. All authors contributed to the article and approved the submitted version.

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REFERENCES

1. Wang Y, Battié MC. Epidemiology of lumbar disc degeneration. In: IM Shapiro, MV Risbud, editors. *The intervertebral disc: Molecular and structural studies of the disc in health and disease*. Vienna: Springer (2014). p. 139–56. doi: 10.1007/978-3-7091-1535-0_9
2. Vergroesen P-PA, Kingma I, Emanuel KS, Hoogendoorn RJW, Welting TJ, van Royen BJ, et al. Mechanics and biology in intervertebral disc degeneration: a vicious circle. *Osteoarthr Cartil*. (2015) 23(7):1057–70. doi: 10.1016/j.joca.2015.03.028
3. Lee SY, Kim T-H, Oh JK, Lee SJ, Park MS. Lumbar stenosis: a recent update by review of literature. *Asian Spine J*. (2015) 9(5):818–28. doi: 10.4184/asj.2015.9.5.818
4. Morishita K, Kasai Y, Uchida A. Clinical symptoms of patients with intervertebral vacuum phenomenon. *Neurologist*. (2008) 14(1):37–9. doi: 10.1097/NRL.0b013e3180dc9992
5. Wu PH, Kim HS, Jang I-T. Intervertebral disc diseases PART 2: a review of the current diagnostic and treatment strategies for intervertebral disc disease. *Int J Mol Sci*. (2020) 21(6):2135. doi: 10.3390/ijms21062135
6. Fernandez-Moure J, Moore CA, Kim K, Karim A, Smith K, Barbosa Z, et al. Novel therapeutic strategies for degenerative disc disease: Review of cell biology and intervertebral disc cell therapy. *SAGE Open Med*. (2018) 6:2050312118761674. doi: 10.1177/2050312118761674
7. Stergar J, Gradisnik L, Velnar T, Maver U. Intervertebral disc tissue engineering: A brief review. *Bosnian J Basic Med Sci*. (2019) 19(2):130–7. doi: 10.17305/bjbms.2019.3778
8. Wang Y, Bai Y, Ma H, Wang S. Comparison of total disc arthroplasty and fusion in treatment of lumbar disc disease. *Medicine*. (2020) 99(35):e22024. doi: 10.1097/MD.0000000000022024
9. Varga PP, Jakab G, Bors IB, Lazary A, Szövérfi Z. Experiences with PMMA cement as a stand-alone intervertebral spacer: Percutaneous cement discoplasty in the case of vacuum phenomenon within lumbar intervertebral discs. *Der Orthopade*. (2015) 44(Suppl 1):S1–S7. doi: 10.1007/s00132-014-3060-1
10. Roosen K. Bone cement as replacement material of cervical disks. *Fortschr Med*. (1982) 100(45):2120–6.
11. Bärlocher CB, Barth A, Krauss JK, Binggeli R, Seiler RW. Comparative evaluation of microdiscectomy only, autograft fusion, polymethylmethacrylate interposition, and threaded titanium cage fusion for treatment of single-level cervical disc disease: a prospective randomized study in 125 patients. *Neurosurg Focus*. (2002) 12(1): 1–7. doi: 10.3171/foc.2002.12.1.5
12. Korinth MC, Krüger A, Oertel MF, Gilsbach JM. Posterior foraminotomy or anterior discectomy with polymethyl methacrylate interbody stabilization for cervical soft disc disease: results in 292 patients with monoradiculopathy. *Spine*. (2006) 31(11):1207–14; discussion 1215–6. doi: 10.1097/01.brs.0000217604.02663.59
13. Kettler A, Wilke H-J, Claes L. Effects of neck movements on stability and subsidence in cervical interbody fusion: an in vitro study. *J Neurosurg*. (2001) 94(1):97–107. doi: 10.3171/spi.2001.94.1.0097
14. Wilke HJ, Kettler A, Goetz C, Claes L. Subsidence resulting from simulated postoperative neck movements: an in vitro investigation with a new cervical fusion cage. *Spine*. (2000) 25(21):2762–70. doi: 10.1097/00007632-200011010-00008
15. Wilke H-J, Kettler A, Claes L. Primary stabilizing effect of interbody fusion devices for the cervical spine: an in vitro comparison between three different cage types and bone cement. *Eur Spine J*. (2000) 9(5):410–6. doi: 10.1007/s005860000168
16. Kiss L, Pal Varga P, Szoverfi Z, Jakab G, Eltes PE, Lazary A. Indirect foraminal decompression and improvement in the lumbar alignment after percutaneous cement discoplasty. *Eur Spine J* [Preprint]. (2019) 28:1441–7. doi: 10.1007/s00586-019-05966-7
17. Yamada K, Nakamae T, Shimbo T, Kanazawa T, Okuda T, Takata H, et al. Targeted therapy for low back pain in elderly degenerative lumbar scoliosis: a cohort study. *Spine*. (2016) 41(10):872–9. doi: 10.1097/BRS.0000000000001524
18. Yamada K, Nakamae T, Nakanishi K, Kamei N, Hiramatsu T, Okuda T, et al. Long-term outcome of targeted therapy for low back pain in elderly degenerative lumbar scoliosis. *Eur Spine J*. (2021) 30:2020–32. doi: 10.1007/s00586-021-06805-4
19. Sola C, et al. Percutaneous cement discoplasty for the treatment of advanced degenerative disk disease in elderly patients. *Eur Spine J*. (2021) 30:2200–8. doi: 10.1007/s00586-018-5547-7
20. Camino-Willhuber G, Mariana Bendersky M, De Cicco FL, Kido G, Duarte MP, Estefan M, et al. Development of a new therapy-oriented classification of intervertebral vacuum phenomenon with evaluation of intra- and interobserver reliabilities. *Global Spine J*. (2021) 11(4):480–7. doi: 10.1177/2192568220913006
21. Eltes PE, Laszlo Kiss L, Bereczki F, Szoverfi Z, Techens C, Jakab G, et al. A novel three-dimensional volumetric method to measure indirect decompression after percutaneous cement discoplasty. *J Orthop Translat*. (2021) 28:131–9. doi: 10.1016/j.jot.2021.02.003
22. Camino-Willhuber G, Kido G, Duarte MP, Estefan M, Bendersky M, Bassani J, et al. Percutaneous cement discoplasty for the treatment of advanced degenerative disc conditions: a case series analysis. *Global Spine J*. (2020) 10(6):729–34. doi: 10.1177/2192568219873885
23. Camino-Willhuber G, Bendersky M, Vilte C, Kido G, Duarte MP, Estefan M, et al. Accuracy of intraoperative neuromonitoring during percutaneous cement discoplasty. *Rev Fac Cienc Med*. (2021) 78(3):257–63. doi: 10.3105310.31053/1853.0605.v78.n3.32619
24. Camino-Willhuber G, Norotte G, Bronsard N, Kido G, Pereira-Duarte M, Estefan M, et al. Percutaneous cement discoplasty for degenerative low back pain with vacuum phenomenon: a multicentric study with a minimum of 2 years of follow-up. *World Neurosurg*. (2021) 155:e210–e217. doi: 10.1016/j.wneu.2021.08.042
25. Tian Q-H, Lu Y-Y, Sun X-Q, Wang T, Wu C-G, Li M-H, Cheng-Ying S. Feasibility of percutaneous lumbar discectomy combined with percutaneous cementoplasty for symptomatic lumbar disc herniation with modic Type I endplate changes. *Pain Physician*. (2017) 20(4):E481–8. PMID: 28535556
26. Tian Q-H, Liu Z-J, Liu H-F, Fang R, Shen R-R, Wang T, Cheng Y-S, et al. Safety and efficacy of percutaneous lumbar discectomy and percutaneous disc cementoplasty for painful lumbar disc herniation in patients over 60 years. *J Vasc Interv Radiol*. (2019) 30(6):894–9. doi: 10.1016/j.jvir.2018.12.018

27. Lewin S, Försth P, Persson C. Low-modulus PMMA has the potential to reduce stresses on endplates after cement discoplasty. *J Funct Biomater*. (2022) 13(1):18. doi: 10.3390/jfb13010018
28. Techens C, Palanca M, Éltes PE, Lazáry Á, Cristofolini L. Testing the impact of discoplasty on the biomechanics of the intervertebral disc with simulated degeneration: An in vitro study. *Med Eng Phys*. (2020) 84:51–9. doi: 10.1016/j.medengphy.2020.07.024
29. Yang L, Kong J, Qiu Z, Shang T, Chen S, Zhao R, Raucci MG, et al. Mineralized collagen-modified PMMA cement enhances bone integration and reduces fibrous encapsulation in the treatment of lumbar degenerative disc disease. *Regen Biomater*. (2020) 7(2):181–93. doi: 10.1093/rb/rbz044
30. Wang B, Shan L, Hao D. Letter to the Editor concerning "Percutaneous cement discoplasty for the treatment of advanced degenerative disk disease in elderly patients" by Sola C, Camino Willhuber G, Kido G et al. Eur Spine J (2018): Doi 10.1007/s00586-018-5547-7. *Eur Spine J*. (2018) 27(7):1665–6. doi: 10.1007/s00586-018-5642-9
31. Camino-Willhuber G, Sola C. Answer to the Letter to the Editor of Biao Wang et al. concerning "Percutaneous cement discoplasty for the treatment of advanced degenerative disk disease in elderly patients" by Sola C, Camino Willhuber G, Kido G et al. Eur Spine J (2018): doi: 10.1007/s00586-018-5547-7. *Eur Spine J*. (2018) 27(7):1667–8. doi: 10.1007/s00586-018-5643-8
32. Lazary A. Expert's Comment concerning Grand Rounds Case entitled "Percutaneous cement discoplasty for the treatment of advanced degenerative disk disease in elderly patients". *Eur Spine J*. (2021) 30(8):2209–10. doi: 10.1007/s00586-020-06568-4
33. Camino-Willhuber G, Bendersky M, Bianchi H, Gruenberg M, Sola C. Reply to A. Lazary's Expert's Comment concerning grand rounds case entitled "Percutaneous cement discoplasty for the treatment of advanced degenerative disk disease in elderly patients" (C. Sola, et al., Eur Spine J; 2021;30(8):2209–2210. doi: 10.1007/s00586-020–06568-4). *Eur Spine J*. (2022) 31(1):205–6. doi: 10.1007/s00586-021-06988-w
34. Lee GY, Lee JW, Choi HS, Oh K-J, Kang H-S. A new grading system of lumbar central canal stenosis on MRI: an easy and reliable method. *Skelet Radiol*. (2011) 40(8):1033–9. doi: 10.1007/s00256-011-1102-x
35. Bartynski WS, Lin L. Lumbar root compression in the lateral recess: MR imaging, conventional myelography, and CT myelography comparison with surgical confirmation. *AJNR Am J Neuroradiol*. (2003) 24(3):348–60. PMID: 12637281; PMCID: PMC7973614
36. Patel RR. *Does patient-specific implant design reduce subsidence risk in lumbar interbody fusion? A bottom up analysis of methods to reduce vertebral endplate stress*. Ph.D. (2018). Available from: https://www.proquest.com/docview/2198656190/abstract/FF7B04C784894A33PQ/1 (Accessed February 3, 2022).

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Circumferential Fusion Employing Transforaminal vs. Direct Lateral Lumbar Interbody Fusion—A Potential Impact on Implants Stability

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Background: Different fusion techniques were introduced in clinical practice in patients with lumbar degenerative disc disease, however, no evidence has been provided on the advantages of one technique over another.

The Objective of This Study: Is to assess the potential impact of circumferential fusion employing transforaminal lumbar interbody fusion (TLIF) vs. direct lateral interbody fusion (DLIF) on pedicle screw stability.

Materials and Methods: This is a single-center prospective evaluation of consecutive 138 patients with degenerative instability of lumbar spinal segments. Either conventional transforaminal lumbar interbody fusion (TLIF) with posterior fusion or direct lateral interbody fusion (DLIF) using cages of standard dimensions, were applied. The conventional open technique was used to supplement TLIF with pedicle screws while percutaneous screw placement was used in patients treated with DLIF. The duration of the follow-up accounted for 24 months. Signs of pedicle screws loosening (PSL) and bone union after fusion were assessed by the results of CT imaging. Fisher's exact test was used to assess the differences in the rate of CT loosening and revision surgery because of implant instability. Logistic regression was used to assess the association between potential factors and complication rate.

Results: The rate of PSL detected by CT and relevant revision surgery in groups treated with TLIF and DLIF accounted for 25 (32.9%) vs. 2 (3.2%), respectively, for the former and 9 (12.0%) vs. 0 (0%) for the latter ($p < 0.0001$ and $p = 0.0043$) respectively. According to the results of logistic regression, a decrease in radiodensity values and a greater number of levels fused were associated with a rise in PSL rate. DLIF application in patients with radiodensity below 140 HU was associated with a considerable decrease in complication rate. Unipolar or bipolar pseudoarthrosis in patients operated on with TLIF was associated with a rise in PSL rate while patients treated with DLIF tolerate delayed interbody fusion formation. In patients treated with TLIF supplementary total or partial posterior fusion resulted in a decline in PSL rate.

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Conclusion: Even though the supplementary posterior fusion may considerably reduce the rate of PSL in patients treated with TLIF, the application of DLIF provide greater stability resulting in a substantial decline in PSL rate and relevant revision surgery.

Keywords: direct lateral interbody fusion, transforaminal lumbar interbody fusion, degenerative diseases, lumbar spine, screw loosening, hounsfield units

INTRODUCTION

Degenerative stenosis of the lumbar spine is a frequently encountered condition in the aging population. Patients with spinal stenosis and segmental instability require decompression of nerve roots and fusion with pedicle screw fixation, which is the most effective solution in those cases (1, 2).

Different techniques were worked out to provide a fusion of altered segments, including PLF (posterolateral fusion), PLIF (posterior lumbar interbody fusion), TLIF (transforaminal lumbar interbody fusion), DLIF (direct lateral interbody fusion), and ALIF (anterior lumbar interbody fusion), however, no evidence has been provided on the advantages and superior outcomes of one technique over another. Even though TLIF is frequently supplemented by PLF to achieve circumferential fusion, those techniques are frequently opposed in relevant studies (3). DLIF using a lateral minimally invasive approach is getting more popular as an effective option to achieve indirect decompression and restoration of sagittal alignment (4). On the other hand, the evidence that the application of DLIF provides better outcomes than direct decompression with TLIF is insufficient especially if short fusion is required, therefore, no clear guidelines exist on the rational application of those techniques (5–8). An additional source of confusion is that the majority of studies focused on comparative analysis of various fusion techniques and the results are based on numeric scores, which can be strongly biased by different reasons that are irrelevant to the applied surgery (9–11).

Altered bone quality has a high prevalence in the elderly adult population and is associated with the most frequently reported complication associated with spinal instrumentation—implant instability development (12, 13). Taking into account concerns associated with a considerable upward trend in the number of fusions performed annually, an optimal surgical strategy should be worked out to decrease the complication rate. For now, there is some evidence that the application of cages with greater surface provides better distribution of load consequently it is expected that patients who are at risk of pedicle screw loosening development (PSL) may benefit from an application of broad cages (14, 15).

The objective of this study is to assess the influence of fusion type on the rate of implant instability development and associated revision surgery.

MATERIALS AND METHODS

This study is a non-randomized single-center prospective evaluation of consecutive 138 patients with degenerative diseases of the lumbar spine and instability of spinal segments, including 33 (23.9%) men and 105 (76.1%) women. The average age of participants at the time of operation was 56 years (SD = 8.7763; range 29–79 years). Patients with axial pain and neurogenic claudication or radiculopathy associated with spinal stenosis were enrolled. Participants underwent spinal instrumentations employing pedicle screw fixation either with transforaminal interbody fusion (TLIF) supplemented with posterior fusion (PF) or direct lateral interbody fusion (DLIF) during the period from 2012 to 2018. The duration of follow-up accounted for 24 months. Radiographic criteria of PSL were used to assess outcomes. This study was reviewed and approved by the local institutional board committee, given that no additional risks were anticipated; all patients signed informed written consent.

The Inclusion Criteria Were

- Presence of degenerative disease of the lumbar spine with unstable spinal segments confirmed by functional radiograms or presence of low-grade symptomatic unstable spondylolisthesis,
- Radiculopathy or neurogenic claudication caused by degenerative diseases of the lumbar spine,
- Axial and radicular pain syndromes with visual analog scale (VAS) over 4 (0–10) and Oswestry Disability Index (ODI) over 40% resistant to repeated conservative treatment during 3 months or neurogenic claudication.

The Exclusion Criteria Were

- High-grade spondylolisthesis (grades 3 and 4),
- Degenerative deformities that required correction of sagittal and frontal balance,
- Tumor-related lesions of the lumbar spine,
- Patients hospitalized for revision surgery,
- Cases with screw malposition and redirection detected on postoperative CT images,
- Patients with different types of fusion applied on different levels (hybrid constructs),
- Cases operated on more than two levels,
- Spinal instrumentation involving lumbosacral segment,
- Patients with the presence of pars interarticularis defects detected on CT images.
- Patients with excessive posterior decompression employing bilateral facet joints removal and laminectomy.

Before surgery, all patients underwent functional X-ray imaging and CT examination. The criterion for spinal instability was the difference in anterior translation on flexion-extension images >3 mm (16). The CT scans were performed from the T12-L5 levels using a single CT scanner (Aquilion 32, Toshiba

Corporation). The scans used a slice thickness of 0.5 mm, covering a scan area of 50 cm. The scan parameters included tube voltage 120 kV, tube current 300 mA, auto mAs range 180–400; 1.0 s/3.0 mm/0.5 × 32, helical-pitch 21.0. Integrated software was used for calculations of bone density (Vitrea Version 5.2.497.5523) incorporating a window width/window level ratio of 2,000/500. During CT examinations, measurements of a vertebral body cancellous bone radiodensity in HU were obtained at the standard level of L3 in the sagittal, axial, and coronal planes. CT examination results were assessed by two independent certified radiologists. Measurements in the axial plane were taken at the level of the middle of the pedicles while those in the sagittal and coronal planes were taken along the geometric center of the vertebral body. Trabecular bone samples were selected using the maximal achievable square without traversing into the cortical bone to calculate bone density in each plane. Out of those figures, an average radiodensity was calculated for each case.

Either TLIF (75 cases—54.3%) with a single cage or DLIF (63 cases—45.7%) were used in this study. The allocation to DLIF or TLIF was based on the consensus of the committee of surgeons and the patient's consent (signed written consent was received from all patients). The applied technique of TLIF was a standard open one with unilateral facet joint removal, the applied DLIF technique was conventional as described previously (17). Cages of standard dimensions were used to perform DLIF and TLIF procedures with a footprint accounting for 1,000 mm^2 for the former (**Figure 1**) and 290 mm^2 for the latter (**Figure 2**). Autograft of locally harvested bone was used to perform TLIF while an allogeneic bone provided by the tissue laboratory of the institution was used for the DLIF procedure. Neither BMP nor other products that accelerate fusion formation were used in this study. The anterior longitudinal ligament has not been transacted during the DLIF procedure. Open TLIF was supplemented with posterior fusion in all cases while only in 15 (23.8%) cases treated with DLIF a posterior fusion was performed using tubular retractors. The technique of posterior fusion included the removal of facet joint capsules, cartilages, and decortication of the adjacent bone. Then the gap formed by capsule and cartilages resection was filled up with a locally harvested bone. Bilateral pedicle screw fixation with polyaxial screws was used in all cases, the applied technique was standard; a strait trajectory for screw placement was used. The conventional open technique was applied to supplement TLIF with pedicle screws while percutaneous screw placement was used in patients treated with DLIF. Pedicle screws were introduced at least to the anterior third of a vertebral body; bicortical screw placement was not used in the enrolled patients. The qualification of a surgeon was at least 7 years of experience.

The duration of the follow-up accounted for 24 months. All patients underwent clinical examination at the time of 3, 6, 12, and 24 months. CT examinations were performed at the time of 6, 12, months after surgery, and regardless of the time if clinical signs of implant failure signs were detected. CT examination was given at the time of 18 and 24 months if unipolar or bipolar non-union was detected according to the results of the former investigation. Interbody fusion was classified according to Tan classification as complete fusion, partial fusion, unipolar pseudoarthrosis, and bipolar pseudoarthrosis (18). Posterior fusion was assessed according to Christiansen's classification of fusion status as total facet joint ankylosing, partial ankylosing, and non-union (19, 20). Cases with PSL detected on CT images were registered. The criterion for screw loosening was a 1-mm or greater radiolucent zone around the screw, a double-halo sign, or both (21). Finally, patient outcomes were classified as either presence of PSL signs, regardless of the number of screws loosened, or the absence of this complication.

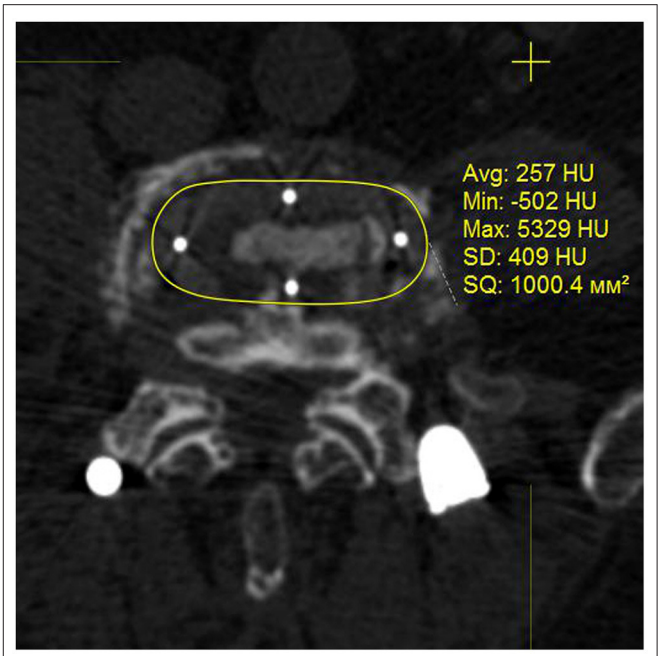

FIGURE 1 | Cage used for DLIF, postoperative CT image in axial plane.

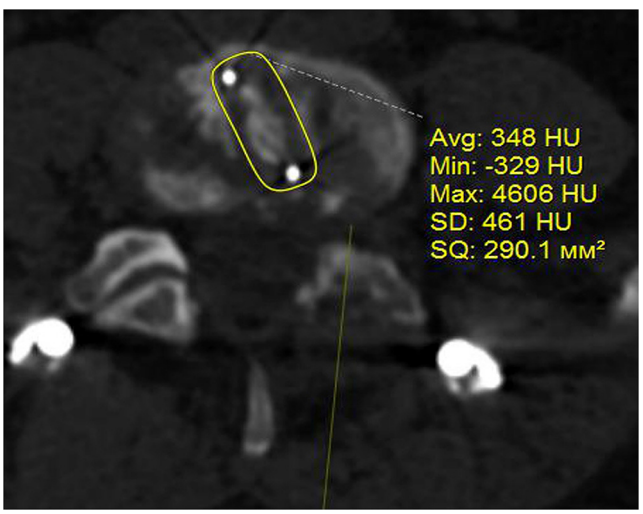

FIGURE 2 | Cage used for TLIF, postoperative CT image in axial plane.

TABLE 1 | Characteristics of the enrolled groups.

Characteristics	Group of patients treated employing DLIF, $n = 63$	Group of patients treated employing TLIF, $n = 75$	Statistical significance
Age, years	M = 56 25–75% [74; 49]	M = 58 25–75% [64; 51]	$p = 0.0705$ Mann-Whitney test
Male to female ratio	12:51	19:56	$p = 0.4183$ (two tailed Fisher's exact test)
Radiodensity, in Hounsfield Units	m = 125,1323 ± 5,0689 SD = 40,2332	m = 118.2551 ± 4.2611 SD = 36.9020	$p = 0.2972$ (Student's *t*-test)
Number of patients with two level fusion	11 (17.5%)	18 (24.0%)	$p = 0.4050$ (two tailed Fisher's exact test)
Patients with radiodensity of cancellous bone below 110 HU	21 (33.3%)	35 (46.7%)	$p = 0.1212$ (two tailed Fisher's exact test)

TABLE 2 | The initial analysis of the results.

	Group of patients treated employing DLIF, $n = 63$	Group of patients treated employing TLIF, $n = 75$	Statistical significance
PSL signs detected on CT images	2 (3.2%)	25 (33.3%)	$p < 0.0001$ (two tailed Fisher's exact test)
Cases with symptomatic pedicle screws instability	0	9 (12%)	$p = 0.0039$ (two tailed Fisher's exact test)
Non-union after interbody fusion – Tan 3 and Tan 4	38 (60.3%)	36 (48.0%)	$p = 0.1722$ (two tailed Fisher's exact test)
Complete and partial posterior fusion	**16 (25.4%)**	**41 (54.6%)**	**$p = 0.0018$ (two tailed Fisher's exact test)**

Bold values were given to highlight statistically significant values.

Cases with PSL were subdivided into clinically significant and asymptomatic ones.

Statistical Analysis

Two-tailed Fisher's exact test was used to test the statistical significance of the observed differences in the rate of PSL and revision surgeries applied. Students' *t*-test for independent samples was used to test the significance of the difference of means; p Values <0.05 were considered statistically significant. Shapiro-Wilk's test was used to test the normality of continuous data distribution. The association between PSL rate and potential risk factors was estimated using logistic regression analysis (a general multivariate logistic regression model was used). Statistica 12 (Statsoft) was used to perform calculations.

TABLE 3 | Parameters of the estimated logistic regression function.

Components of regression model	Regression coefficient and its statistical significance	OR per unit change with 95% CI
Intercept	0.5594 $p = 0.7701$	
Radiodensity in HU	**0,0356** **$p = 0.0077$**	**0.9650** **[0.9399; 0.9909]**
Number of levels fused	**1.9043** **$p = 0.0206$**	**6.7148** **[1.3193; 31.1754]**
DLIF application in patients with cancellous bone radiodensity below 140 HU	**−3.7270** **$p = 0.0182$**	**0.0241** **[0.0011; 0.5455]**
Unipolar and bipolar pseudoarthrosis in patients treated with TLIF	**2.5825** **$p = 0.0018$**	**13.2308** **[2.6669; 65.6408]**
Partial and total posterior fusion in patients treated with TLIF	**−3.4008** **$p = 0.0010$**	**0.0334** **[0.0045; 0.2445]**
Unipolar and bipolar pseudoarthrosis in patients treated with DLIF	0.5482 $p = 0.6170$	1.7302 [0.1988; 15.0560]
Partial and total posterior fusion in patients treated with DLIF	−0.0299 $p = 0.9820$	0.9705 [0.0708; 13.3068]

Bold values were given to highlight statistically significant values.

RESULTS

A total number of 138 patients with degenerative diseases of the lumbar spine were enrolled. The characteristics of the enrolled groups of patients are given in **Table 1**. According to the results of the analysis, no statistically significant differences were detected between the enrolled groups of patients.

By the end of the follow-up period, CT signs of PSL were detected in 27 (19.6%) patients, out of those only 9 (6.5%) were symptomatically deteriorating with axial pain VAS of more than 4 and ODI scores over 40; the latter 9 patients underwent revision surgery. Patients with clinically significant instability presented with either multiple pedicle screws instability or bilateral one-level screw loosening along with either unipolar or bipolar interbody pseudoarthrosis (Tan 3 or Tan 4) with complete posterior non-union. The primary analysis of the results with a breakdown by groups is given in **Table 2**.

According to the results given in **Table 2**, the rate of pedicle screw loosening detected on CT and the rate of revision surgery was greater in the group of patients treated with TLIF. Relatively high prevalence of CT loosening signs, anterior and posterior non-union can be explained by a considerable proportion of patients with radiodensity below the threshold of 110 HU which corresponds to 90% specificity of osteoporosis detection. The number of those cases accounted for 56 (40.5%) in the total cohort of enrolled patients. It was expected that the application of autograft may favor interbody fusion formation in patients treated employing TLIF, however, the difference between two groups in Tan 3 and Tan 4 rate pseudoarthrosis turned out statistically insignificant. It should be mentioned, that in 16 cases a spontaneous posterior fusion was evaluated in the group of patients treated with DLIF.

To estimate a relative contribution of the applied fusion technique to screw loosening, to detect other contributing factors, and to assess their interaction, a general logistic regression analysis was used. The dependent variable was the presence of CT signs of PSL. Finally, the model with the best subsets of variables that provides the best explanatory value was chosen. Mining the data, it has been estimated that the best model can be estimated only if higher-order effects were taken into account. The parameters of the estimated general multivariate logistic regression model with the best characteristics are present in **Table 3**.

The overall goodness of fit of the estimated general multivariate model was $\chi^2 = 69{,}722$, $p < 0.0001$. According to the results of the analysis, a decrease in radiodensity values and a greater number of levels fused were associated with a rise in pedicle screw instability development rate. DLIF application in patients with radiodensity below 140 HU was associated with a considerable decrease in PSL rate. Unipolar or bipolar pseudoarthrosis in patients operated on applying TLIF was associated with a rise in the PSL rate while non-union grade 3 and 4 was not associated with an increment in PSL rate in a group of patients treated with DLIF. In patients treated with TLIF, a supplementary total or partial posterior fusion resulted in a decline in PSL rate conversely this factor turned out insignificant in patients treated with DLIF. The estimated logistic regression model had a specificity accounting for 95.5%, sensitivity of 68.0%, and preciseness of classification 90.4%.

DISCUSSION

Even though pedicle screw fixation with interbody fusion has been proven to be the most effective treatment option for patients with spinal stenosis and segment instability, the rate of instrumentation failure caused by altered bone quality remains considerable given the high prevalence of the latter in the elderly adult population (21–23). Different diagnostic tools are used to detect patients who are at risk of implant instability development and the application of radiodensity in HU becomes popular because those figures correlate with bone mechanical properties. Furthermore, it has been defined that thresholds of 110 HU and 135 HU have maximal specificity for osteoporosis and osteopenia detection, respectively (24–26). The initial analysis demonstrates a high prevalence of cases with altered bone quality that accounted for 54 (41.2%) in the enrolled group. Those figures explain a relatively high rate of screw loosening and non-union detected during the follow-up period.

To achieve substantial stability of the altered segment various types of interbody fusion were suggested, out of those the most frequently used are PLIF, TLIF, DLIF, OLIF, and ALIF (4). Despite a considerable number of relevant works published, no clear guidelines were worked out for the rational application of those techniques. The source of additional confusion to the reported results is that a hefty majority of relevant studies are based on the dynamics of subjective numeric scores assessment. Apparently, those studies have evident weak points. Firstly, the application of numeric scores is not standardized yet (8). Secondly, the results of those studies can be influenced by many irrelevant to the applied surgery causes, including the accuracy of diagnoses, socioeconomic, behavioral, psychological factors, sacroiliac joints dysfunction, and adjacent level degeneration (9, 10, 27, 28). To avoid bias relevant to the application of subjective numeric scores, radiographic signs of PSL were used in the current study. Considering that signs of CT loosening can be asymptomatic, questioning their clinical relevance, the rate of clinically significant loosening that requires revision surgery was taken as an additional criterion for the assessment of the results.

According to the results of research on biomechanics, the most reliable mechanism of PSL are micro-movements caused by craniocaudal toggling and rotational stress that increase the load to the zone of the bone-screw interface (29). To minimize micro-movements that cause PSL the application of the most stable type of fusion is required. By using biomechanical tests some evidence has been provided, that application of broad cages may lead to better load distribution, decreasing stress on screws, rods, and endplates (13, 30). The results of our study confirm the clinical relevance of biomechanical studies since a considerable decline in the rate of PSL detected was associated with DLIF application. The observed effect achieves maximum in patients with radiodensity of cancellous bone below 140 HU. According to our results, unipolar or bipolar pseudoarthrosis is a significant factor promoting PSL in patients operated on applying TLIF while those treated with DLIF tolerate delay in interbody fusion formation. Although posterior fusion is frequently opposed to interbody fusion, it has been defined that circumferential fusion using both listed provides a greater success rate in patients with degenerative diseases of the lumbar spine (31–34). Our findings demonstrate that total and even partial posterior fusion is associated with a decline in PSL rate if TLIF was employed, conversely, posterior fusion turned out to be an insignificant factor in patients treated with DLIF, consequently, additional posterior fusion is not required in this group of patients.

Eventually, the main findings of the analysis demonstrate that the application of DLIF may provide a considerable decline in the rate of PSL detected by CT, especially in patients with radiodensity below 140 HU. Those findings can be explained by a beneficial distribution of forces alleviating stress on the screw-bone interface. A statistically significant difference in clinically significant loosening rate supports the conclusion that the observed effect of DLIF application is clinically relevant and

has thepotential as a beneficial option in patients who are at risk of implant instability development.

LIMITATIONS

This study has limitations that should be acknowledged. Firstly, this study is not a randomized one; secondly, the number of participants is relatively small to provide a robust regression model suitable for instrumentation failure prediction. On the other hand, the results of the study provide evidence that the application of DLIF with a broad cage results in a decline in the rate of pedicle screw loosening and associated revision surgery. Also, a potential bias was addressed in this study associated with heterogeneity in bone properties, number of levels fused, and application of supplementary posterior fusion.

CONCLUSION

Even though the supplementary posterior fusion may considerably reduce the rate of pedicle screw loosening in patients treated with TLIF, the application of DLIF provide greater stability resulting in a substantial decline in PSL rate and relevant revision surgery.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Local IRB Committee of Privolzhsky Research Medical University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AB contributed to study concept and design. SK contributed to data collection, data mining, and manuscript editing. AL contributed to data collection and data mining. SM supervised the project and reviewed the manuscript. All authors contributed to the article and approved the submitted version.

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REFERENCES

1. Resnick DK, Watters WC, Sharan A, Mummaneni PV, Dailey AT, Wang JC, et al. Guideline update for the performance of fusion procedures for degenerative disease of the lumbar spine. Part 9: lumbar fusion for stenosis with spondylolisthesis. *J Neurosurg Spine.* (2014) 21:54–61. doi: 10.3171/2014.4.SPINE14274
2. Wang JC, Dailey AT, Mummaneni PV, Ghogawala Z, Resnick DK, Watters C III, et al. Guideline update for the performance of fusion procedures for degenerative disease of the lumbar spine. Part 8: lumbar fusion for disc herniation and radiculopathy. *J Neurosurg Spine.* (2014) 21:48–53. doi: 10.3171/2014.4.SPINE14271
3. Bozkurt G, Isikay I, Hanalioglu S. Radiological and clinical comparison of posterolateral fusion and transforaminal interbody fusion techniques in degenerative lumbar stenosis. *World Neurosurg.* (2018) 116:e1060–e1065. doi: 10.1016/j.wneu.2018.05.165
4. Formica M, Quarto E, Zanirato A, Mosconi L, Vallerga D, Zotta I, et al. Lateral lumbar interbody fusion: what is the evidence of indirect neural decompression? A systematic review of the literature. *HSS J.* (2020) 16:143–54. doi: 10.1007/s11420-019-09734-7
5. Mobbs RJ, Phan K, Malham G, Seex K, Rao PJ. Lumbar interbody fusion: techniques, indications and comparison of interbody fusion options including PLIF, TLIF, MI-TLIF, OLIF/ATP, LLIF and ALIF. *J Spine Surg.* (2015) 1:2–18. doi: 10.3978/j.issn.2414-469X.2015.10.05
6. Joseph JR, Smith BW, La Marca F, Park P. Comparison of complication rates of minimally invasive transforaminal lumbar interbody fusion and lateral lumbar interbody fusion: a systematic review of the literature. *Neurosurg Focus.* (2015) 39:E4. doi: 10.3171/2015.7.FOCUS15278
7. Cho JY, Goh TS, Son SM, Kim DS, Lee JS. Comparison of anterior approach and posterior approach to instrumented interbody fusion for spondylolisthesis: a meta-analysis. *World Neurosurg.* (2019) 129:e286–e293. doi: 10.1016/j.wneu.2019.05.130
8. Keorochana G, Setrkraising K, Woratanarat P, Arirachakaran A, Kongtharvonskul J. Clinical outcomes after minimally invasive transforaminal lumbar interbody fusion and lateral lumbar interbody fusion for treatment of degenerative lumbar disease: a systematic review and meta-analysis. *Neurosurg Rev.* (2018) 41:755–70. doi: 10.1007/s10143-016-0806-8
9. Winebrake JP, Lovecchio F, Steinhaus M, Farmer J, Sama A. Wide variability in patient-reported outcomes measures after fusion for lumbar spinal stenosis: a systematic review. *Global Spine J.* (2020) 10:209–15. doi: 10.1177/2192568219832853
10. Baber Z, Erdek MA. Failed back surgery syndrome: current perspectives. *J Pain Res.* (2016) 9:979–87. doi: 10.2147/JPR.S92776
11. Clancy C, Quinn A, Wilson F. The aetiologies of failed back surgery syndrome: a systematic review. *J Back Musculoskelet Rehabil.* (2017) 30:395–402. doi: 10.3233/BMR-150318
12. Zou D, Sun Z, Zhou S, Zhong W, Li W. Hounsfield units value is a better predictor of pedicle screw loosening than the T-score of DXA in patients with lumbar degenerative diseases. *Eur Spine J.* (2020) 29:1105–11. doi: 10.1007/s00586-020-06386-8
13. St Jeor JD, Jackson TJ, Xiong AE, Freedman BA, Sebastian AS, Currier BL, et al. Average lumbar hounsfield units predicts osteoporosis-related complications following lumbar spine fusion. *Global Spine J.* (2020) 2192568220975365. doi: 10.1177/2192568220975365. [Epub ahead of print].
14. Zhang T, Bai S, Dokos S, Cheung JP, Diwan AD. XLIF interbody cage reduces stress and strain of fixation in spinal reconstructive surgery in comparison with TLIF cage with bilateral or unilateral fixation: a computational analysis. *Annu Int Conf IEEE Eng Med Biol Soc.* (2019) 2019:1887–90. doi: 10.1109/EMBC.2019.8856592
15. Lu T, Lu Y. Comparison of biomechanical performance among posterolateral fusion and transforaminal, extreme, and oblique lumbar interbody fusion: a finite element analysis. *World Neurosurg.* (2019) 129:e890–e899. doi: 10.1016/j.wneu.2019.06.074
16. Leone A, Guglielmi G, Cassar-Pullicino VN, Bonomo L. Lumbar intervertebral instability: a review. *Radiology.* (2007) 245:62–77. doi: 10.1148/radiol.2451051359
17. Spiker WR, Goz V, Brodke DS. Lumbar interbody fusions for degenerative spondylolisthesis: review of techniques, indications, and outcomes. *Global Spine J.* (2019) 9:77–84. doi: 10.1177/2192568217712494
18. Tan GH, Goss BG, Thorpe PJ, Williams RP. CT-based classification of long spinal allograft fusion. *Eur Spine J.* (2007) 16:1875–81. doi: 10.1007/s00586-007-0376-0
19. Christensen FB, Laursen M, Gelineck J, Eiskjaer SP, Thomsen K, Bünger E, et al. Interobserver and intraobserver agreement of radiograph interpretation

with and without pedicle screw implants: the need for a detailed classification system in posterolateral spinal fusion. *Spine.* (2001) 26:538–43. doi: 10.1097/00007632-200103010-00018
20. Lehr AM, Oner FC, Delawi D, Stellato RK, Hoebink EA, Kempen DHR, et al.C. Dutch Clinical Spine Research Group. Increasing Fusion Rate Between 1 and 2 Years After Instrumented Posterolateral Spinal Fusion and the Role of Bone Grafting. *Spine.* (2020) 45:1403–10. doi: 10.1097/BRS.0000000000003558
21. Galbusera F, Volkheimer D, Reitmaier S, Berger-Roscher N, Kienle A, Wilke J, et al. Pedicle screw loosening: a clinically relevant complication? *Eur Spine J.* (2015) 24:1005–16. doi: 10.1007/s00586-015-3768-6
22. Wu ZX, Gong FT, Liu L, Ma ZS, Zhang Y, Zhao X, et al. A comparative study on screw loosening in osteoporotic lumbar spine fusion between expandable and conventional pedicle screws. *Arch Orthop Trauma Surg.* (2012) 132:471–6. doi: 10.1007/s00402-011-1439-6
23. Bredow J, Boese CK, Werner CM, Siewe J, Löhrer L, Zarghooni K, et al.J. Predictive validity of preoperative CT scans and the risk of pedicle screw loosening in spinal surgery. *Arch Orthop Trauma Surg.* (2016) 136:1063–7. doi: 10.1007/s00402-016-2487-8
24. Khan SN, Warkhedkar RM, Shyam AK. Analysis of Hounsfield unit of human bones for strength evaluation. *Procedia Mater Sci.* (2014) 6:512–9. doi: 10.1016/j.mspro.2014.07.065
25. Schwaiger BJ, Gersing AS, Baum T, Noël PB, Zimmer C, Bauer S, et al. Bone mineral density values derived from routine lumbar spine multidetector row CT predict osteoporotic vertebral fractures and screw loosening. *AJNR Am J Neuroradiol.* (2014) 35:1628–33. doi: 10.3174/ajnr.A3893
26. Zaidi Q, Danisa OA, Cheng W. Measurement techniques and utility of hounsfield unit values for assessment of bone quality prior to spinal instrumentation: a review of current literature. *Spine.* (2019) 44:E239–E244. doi: 10.1097/BRS.0000000000002813
27. Peh W. Image-guided facet joint injection. *Biomed Imaging Interv J.* (2011) 7:e4. doi: 10.2349/biij.7.1.e4
28. Bokov A, Isrelov A, Skorodumov A, Aleynik A, Simonov A, Mlyavykh S, et al. An analysis of reasons for failed back surgery syndrome and partial results after different types of surgical lumbar nerve root decompression. *Pain Physician.* (2011) 14:545–57. doi: 10.36076/ppj.2011/14/545
29. Mizuno T, Kasai Y, Sakakibara T, Yoshikawa T, Inaba T. Biomechanical study of rotational micromovement of the pedicle screw. *Springerplus.* (2016) 5:1016. doi: 10.1186/s40064-016-2694-3
30. Cadman J, Sutterlin C III, Dabirrahmani D, Appleyard R. The importance of loading the periphery of the vertebral endplate. *J Spine Surg.* (2016) 2:178–84. doi: 10.21037/jss.2016.09.08
31. Høy K, Bünger C, Niederman B, Helmig P, Hansen ES, Li H, et al. Transforaminal lumbar interbody fusion (TLIF) versus posterolateral instrumented fusion (PLF) in degenerative lumbar disorders: a randomized clinical trial with 2-year follow-up. *Eur Spine J.* (2013) 22:2022–9. doi: 10.1007/s00586-013-2760-2
32. Kang YN, Ho YW, Chu W, Chou WS, Cheng SH. Effects and safety of lumbar fusion techniques in lumbar spondylolisthesis: a network meta-analysis of randomized controlled trials. *Global Spine J.* (2021) 12:493–502. doi: 10.1177/2192568221997804
33. Rao PJ, Mobbs RJ. The "TFP" fusion technique for posterior 360° lumbar fusion: a combination of open decompression, transforaminal lumbar interbody fusion, and facet fusion with percutaneous pedicle screw fixation. *Orthop Surg.* (2014) 6:54–9. doi: 10.1111/os.12086
34. Salehi SA, Tawk R, Ganju A, LaMarca F, Liu JC, Ondra SL. Transforaminal lumbar interbody fusion: surgical technique and results in 24 patients. *Neurosurgery.* (2004) 54:368–74. doi: 10.1227/01.NEU.0000103493.25162.18

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METHODS
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Minimally-Invasive Assisted Robotic Spine Surgery (MARSS)

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Minimally-Invasive robotic spine surgery (MARSS) has expanded the surgeons armamentarium to treat a variety of spinal disorders. In the last decade, robotic developments in spine surgery have improved the safety, accuracy and efficacy of instrumentation placement. Additionally, robotic instruments have been applied to remove tumors in difficult locations while maintaining minimally invasive access. Gross movements by the surgeon are translated into fine, precise movements by the robot. This is exemplified in this chapter with the use of the da Vinci robot to remove apical thoracic tumors. In this chapter, we will review the development, technological advancements, and cases that have been conducted using MARSS to treat spine pathology in a minimally invasive fashion.

Keywords: robotic, minimally invasive spine surgery (MISS), mazor X, stereotactic transformation, minimally-invasive robotic spine surgery (MARSS), da Vinci

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INTRODUCTION

Spine surgery has experienced tremendous innovation and evolution over the last 50 years, including the implementation of novel technologies, the development of new procedures, and the expansion of biologics. Image guided surgery is one such technique that was developed due to a need to improve surgical precision and accuracy in complex cases. As image guided surgery has become more widely available, these technologies have been applied to the field of robotic surgery (1–5). Initially robotic surgery was a method to translate a virtually planned procedure into a localized surgical process, as seen in stereotactic cranial surgery. Many elements impact the fidelity of robotic surgery, including meticulous case selection, optimizing the method of pre-operative imaging, and 10–16, collaborating with industry to develop these systems. Starting in 2000, several adaptations in robotic and stereotactic systems were made that have led to the development of robotic interfaces that are currently being used to treat spine pathology (6).

One of the factors that prompted the development of robotics in spine surgery was the relatively steep learning curve of minimally invasive spine approaches. Due to the manual dexterity required to operate effectively within a narrow working corridor, manual minimally invasive spine surgery presents a unique challenge (7–9). However, there are certain procedures where the application of robotics presents a niche opportunity to improve surgical accuracy and efficiency, such as placement of percutaneous pedicle screws (10–16).

Consequently, image guided spine surgery has become a valuable tool for performing minimally invasive spine surgeries (17, 18). Several commercial systems have become available for cranial and spine procedures, with thousands of units being used in centers across the globe (18–20). The first reported robotic application in the neurosurgical field was for stereotactic brain biopsy utilizing the PUMA robot system. (PUMA 200) (6, 21) De Souza published the first spine robot in practice using the spine assist system (Mazor Robotics Ltd., Caesarea, Israel), which received FDA approval in 2004 (22). In 2008, the application of robotics in spine surgery was expanded with approval of NeuroMate (Integrated Surgical Systems, Sacramento, California, US). As the interest in these systems grew, further advancements utilizing tele-surgical robots including da Vinci (da Vinci Technologies) were developed (23).

In the United States, there are several commercial spine robots available. These include the Mazor X, (Mazor X Stealth Station, Medtronic), Globus XPS (GPS Excelsius GPS® Robotic Navigation Platform | Globus Medical) and Rosa technologies (ROSA ONE® Brain-Zimmer Biomet) (**Figures 1**–**5**).

These technologies have progressed from simple robotic interfaces to minimally-assisted robotic spine surgery (MARSS). There is a growing interest in the use of robotics with telepresence systems, including the da Vinci robot. Joseph et al reported the use of robotics in spinal instrumentation and identified variables such as precision of screw placement, surgeon learning curve, radiation exposure, and reasons for robotic failure, making note of the high degree of accuracy that can be achieved using robotic instrumentation techniques (24). These aspects of robotic surgery underscore the growing relevance of robotic techniques in the treatment of spinal pathology.

METHODOLOGY

Most of the robotic approaches in thoracolumbar spine are built as ordered steps to establish an intuitive work flow. The preoperative imaging include X-rays, computer tomography (CT), and magnetic resonance imaging (MRI). Specific protocols are used to preset software capabilities to optimize this process. Initial software interactions allow the surgeon to plan the procedure utilizing common surface rendering, hybrid imaging selection, image fusion and trajectory definition. Once the proposed plan has been defined, the incision is made using the robotic assisted approach. When tumor resection is required, planning steps can be created to allow safe removal of the identified structure through a minimally invasive robotic method. Vasculature can

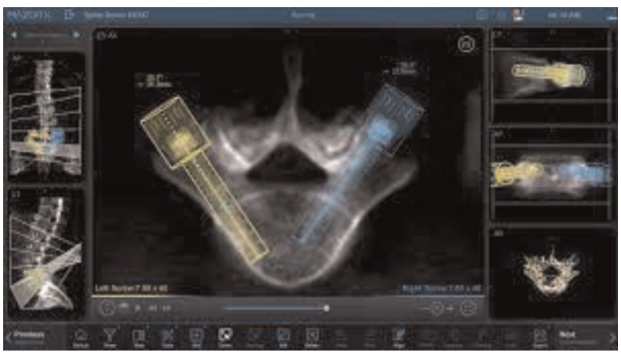

FIGURE 2 | Software interaction with Mazor X, including pedicle screw selection along with optimization of construct definition. Proper pedicle screw diameter and length can be selected to conform to the patient's individual anatomy based on pre-operative imaging using the work-station.

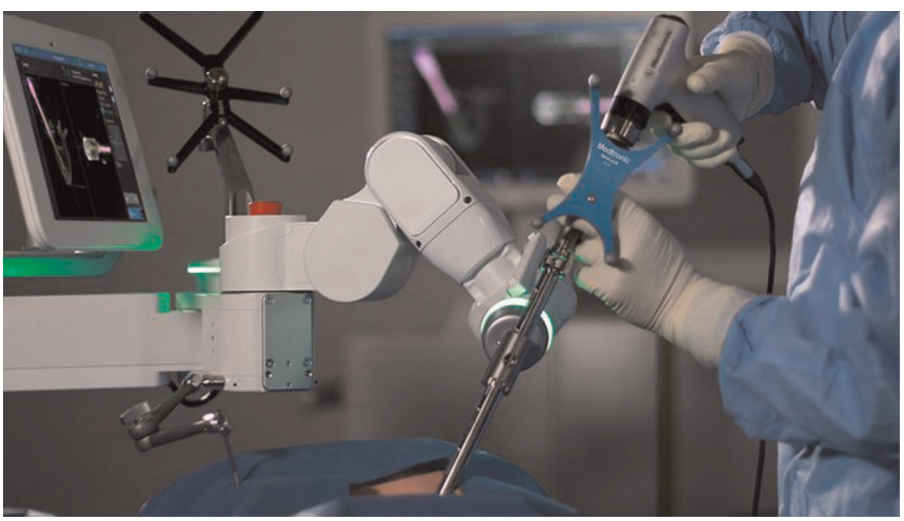

FIGURE 1 | Photo of Mazor X (Mazor Stealth technologies, Medtronic). A commercial system designed to extend the working options, including imaging processing and robot-based interaction.

FIGURE 3 | Mazor X in working position during drilling of the pedicle for pedicle screw application.

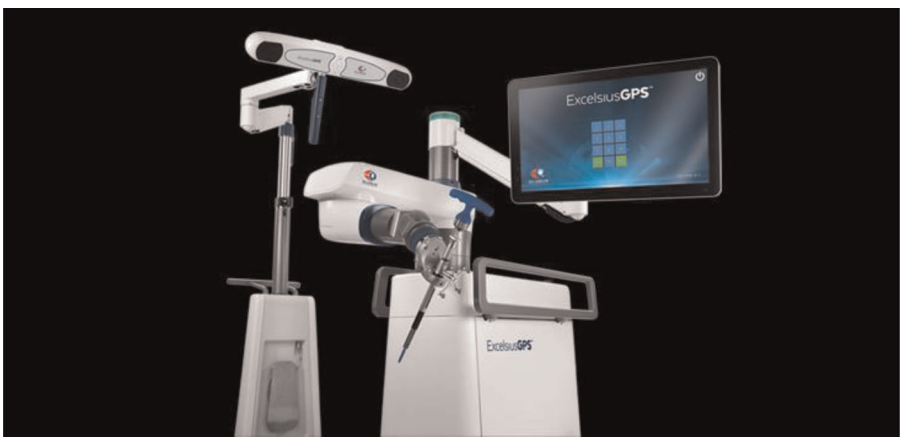

FIGURE 4 | Excelcius GPS equipment. A robotic arm-based technology along with multiple intuitive functions for working environment.

be clearly delineated to augment the safety of the surgical approach. In thoracotomy, robotic approaches can identify safe paths of entry into the chest cavity, and multiple thoracoscopic ports can be created according to the intrinsic patient pathology. The entry point for pedicle screw placement, trajectory definition for patients with challenging anatomy, and rod, pedicle screw, and interbody cage selection can all be done through the robotic software without utilizing physical trial implants. Each robotic system, given its proprietary design, affords surgeons the freedom of choice to choose their preferred system.

MAZOR X- TECHNOLOGIES

The commercially available Mazor X -Stealth Edition represents one of the most advanced technologies in the field. A truly hybrid system, this instrument includes a combination of image guided surgery and robotic arm capabilities. Most of the robotic systems in use today follow a similar setup process as outlined below.

Imaging Acquisition and Preoperative Planning

Pre-operative image acquisition is performed using fluoroscopic x-rays and computed tomography (CT). The images are then transferred to the Mazor X workstation where surgical planning software allows a multiplicity of functions, including 3D reconstruction and surgical rehearsal. These functions allow for vertebral pedicle measurements, anatomical pedicle angulation, and pedicle screw implant selection. The list of pedicle screws can be optimized using a series of planning

FIGURE 5 | ROSA technologies (Zimmer Spine Inc.).

steps and parameters including trajectories, measurements, and construct alignment. On the day of the procedure, the working plan can be transferred to the robotic guidance system. Recent adaptations allow the use of intraoperative CT scanning as well (O-Arm, Medtronic technologies) (**Figures 1**–**3**).

Patient Setup, Preoperative Preparation

The conventional methodology of spine surgery is followed during preoperative preparation: the patient is placed under general anesthesia, transferred to the operating table (Jackson table), and adequately padded. The appropriate draping system for the robot is used, and following the surgical preparation and draping, a guidance device is attached to the patient's spine or iliac crest. We routinely use electromyographic (EMG) neuromonitoring to record pertinent nerve root potentials during the surgical procedure. The operation is then carried out in a linear, step-wise fashion. These subsequent steps of MARSS include:

- Placement of the robotic arm in the proper position.
- Obtaining additional AP and oblique views for registration and stereotactic transformation (these images allow surface matching with the preoperative imaging set).
- Activation of the surgical robot interaction.
- Placement of the surgical drill in position to start the procedure.
- Replacing the starting drill with a serrated drill.
- Removal of the retractor and replacement with robotic extender to be used for pedicle screw placement.
- Positioning a Kirschner pin into the drilled hole.
- Manual placement pedicle screws onto the robot following the defined trajectory.
- Tapping the proposed trajectory, and continuing with pedicle screw placement.
- Correction, reduction, compression done in a specific order.
- Additional decompression, osteotomies or rod tightening done as required.
- Bone fusion including decorticating and drilling along with use of bone substitutes.

EXCELCIUS ROBOTIC APPLICATIONS

The robotic positioning system (Excelsius GPS, Globus Medical, Inc. Audubon, PA) are compatible with several imaging modalities, including a preoperative CT, an intraoperative CT or fluoroscopy. As in any camera based-tracking technology, it

is important to establish a patient's reference base for calibration purposes (25). The steps that need to be followed are described below (**Figure 4**).

Preoperative CT

A computed tomography (CT) scan of all spinal levels using 1 mm cuts is critical to cover the proposed surgical levels. All images are subsequently transferred to the workstation for planning and creation of the virtual environment. The CT data set is usually transferred into the robotic positioning system and registration is subsequently completed for all vertebral levels.

Intraoperative CT Methodology

The stack of images along with the coordinate system are transferred to the planning module. (O-arm, Medtronic SNT, Louisville, CO, USA) The installed software allows multiple trajectories to be planned for pedicle screw insertion. The entry point, trajectory, pedicle screw selection and optimization are done using the planning module.

Surgical Technique

The initial portion of the procedure requires foot pedal activation for robotic arm movement. Once the entry point is defined, a pointing tube connector can be applied. A stab incision is done accordingly. Fascia and soft tissue dissection allow the entry point and initial trajectory to be executed. A final position to entry point is marked, and an initial working drill is inserted to the proposed trajectory. Electrophysiological monitoring is continuously done. A pedicle screw is inserted using a simple passing to the planned trajectory. Once all pedicle screws are completed, rods are passed through the connecting incision. Bolts secure the rod to the construct. Intraoperative images can be done at any point to verify the positioning of screws and rods. Decompression can be completed along with interbody placement.

ROSA SYSTEM ROBOTIC APPROACHES

The imaging process and software interaction follow the proprietary design. Each technology confers additional advantages and interactions that facilitate the working process. Rosa technologies encompass a family of robotic equipment with several years in the market that display some unique features useful in spine surgery. These technologies allow for 6 degrees of movement in the robotic arm once the planning process has been completed, and an advanced integrated software allows multiple intuitive functions to be applied during the planning of working trajectories (**Figure 5**).

DA VINCI ROBOT TECHNOLOGIES

Since its introduction into the surgical arena in 2000, the Da Vinci robot (Da Vinci Technologies) has undergone a series

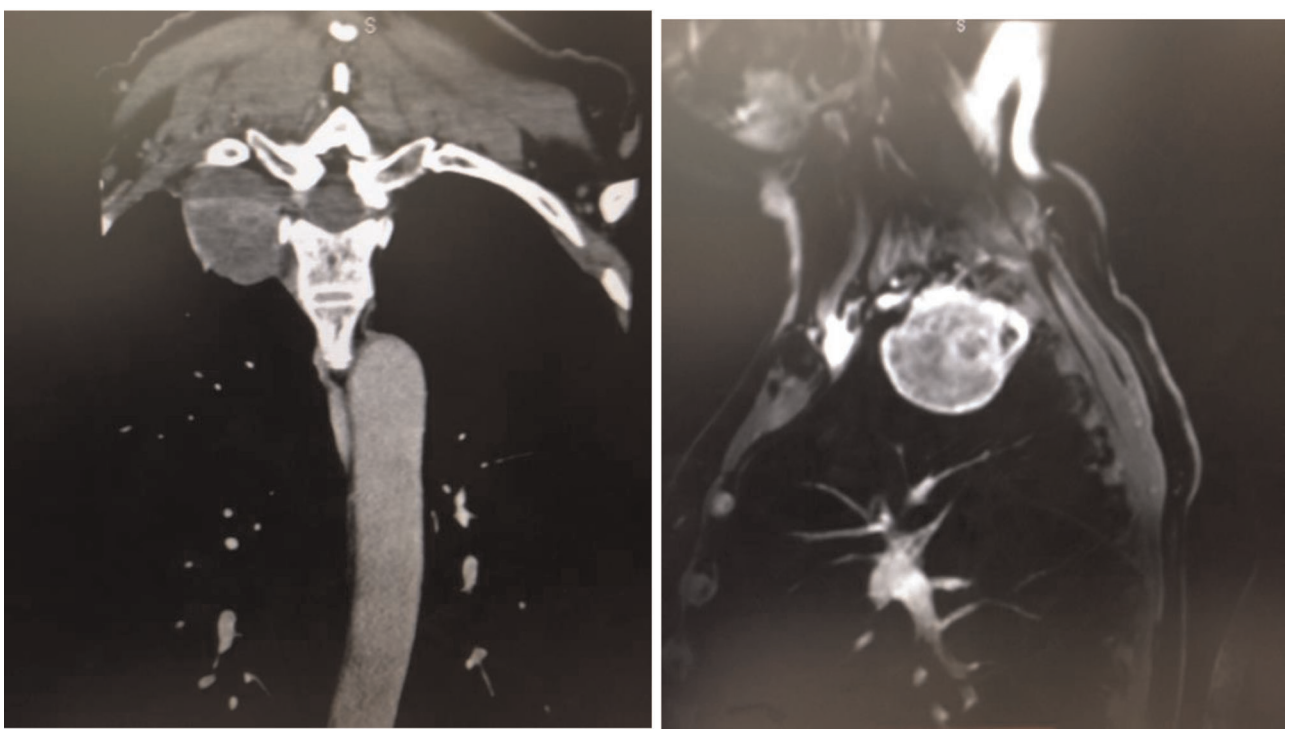

FIGURE 6 | Pre-operative coronal and sagittal thoracic MRI images showing high apical chest tumor. Thin slice CT images can be very helpful in identifying the neural foramen of tumor origin. This is critical in safely detaching the tumor from the spinal canal before final removal through the chest cavity.

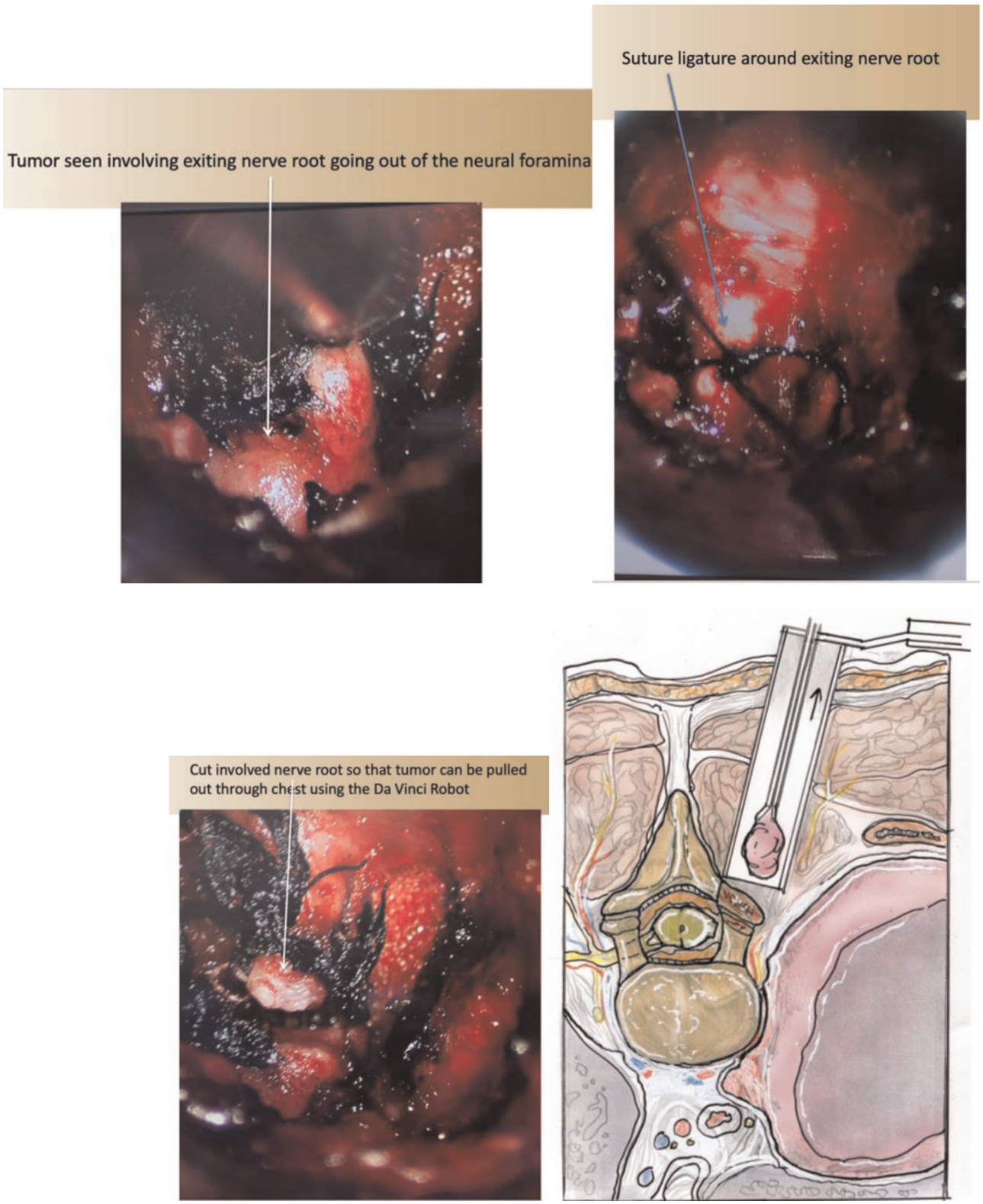

FIGURE 7 | (**A**) Intra-operative photo showing (**A**) tumor extending outside the neural foramen, (**B**) silk suture ligature around the nerve giving rise to the tumor, (**C**) ligation of the nerve leading to the tumor. (**D**) Illustration of removal of intra-spinal canal portion of the tumor via a posterior approach through a tubular retractor.

of developments to expand the range of utilization (26, 27). The telepresence modality utilized by the Da Vinci robot makes it one of the most versatile and utilitarian surgical instruments (28). An increasing number of publications exist that aim to broaden the surgical applications of this instrument (29–32).

Pre-Operative Planning

Patients typically present with apical thoracic lesions. The ideal patient in our opinion has well circumscribed lesions such at schwannomas or neurofibromas. As more efficient techniques for spine surgery using the da Vinci system are developed, the indications for utilizing this technology will expand accordingly. For patients presenting with apical thoracic schwannomas, imaging studies include contrast thoracic spinal MRI and CT to accurately identify the level of origin and determine the neural foramen from which the tumor originates (**Figure 6**).

A sagittal CT starting at the sacrum can help to accurately determine the level of the lesion. For determination of the proper surgical level, the following images are ordered: chest X-ray, thoracic and lumbar anteroposterior (AP) and lateral images. Intra-operative fluoroscopy is used to confirm the level of the lesion by counting vertebral bodies starting at the sacrum or ribs on the AP chest view. Alternatively, an opaque marker can be placed pre-operatively by interventional radiology to help identify the proper location of the tumor. In cases of removal of thoracic schwannomas, no implant instrumentation is needed.

Surgical Technique and Case Examples

The patient is initially positioned in the prone position on a Jackson table with all pressure points adequately padded. A Jackson table allows for unencumbered localization of the lesion using intra-operative fluoroscopy. Double lumen intubation is done to allow for collapse of the lung on the side used for the thoracic approach. Intra-operative electro-physiologic monitoring is used to measure somatosensory evoked potentials and motor evoked potentials. AP and lateral fluoroscopy are used to help localize the level. An incision is then made lateral to the midline based on pre-operative image analysis, and is typically only 2–3 cm from the midline. The fascia is cut, and a muscle dilating technique is used to approach the thoracic spine over which a tubular retractor is placed.

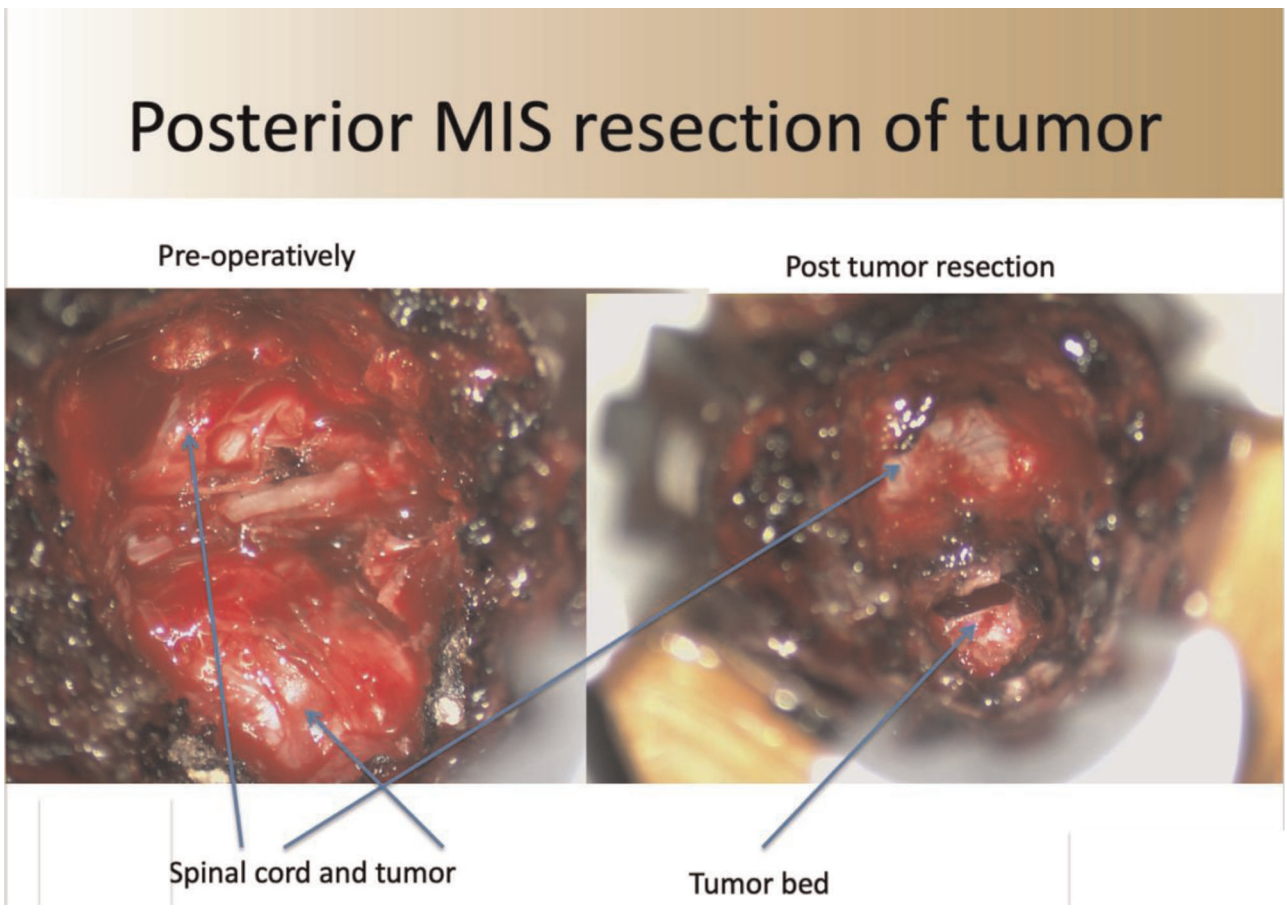

FIGURE 8 | Intra-operative photos after minimally invasive posterior approach (**A**) tumor and intra-canal neural foramen tumor exposed and (**B**) after resection of the tumor with residual tumor bed.

Under microscopic visualization, the ipsilateral lamina and facet are exposed. A bone cutting drill with an M8 cutting burr is used to perform an adequate ipsilateral laminectomy and facetectomy, thereby exposing the tumor within the neural foramen and spinal canal. The contralateral aspect of the spine is not dissected. The drilled bone is collected using a BoneBac Press (Thompson MIS/Bonebac, Salem, NH) (10). This local morselized autograft bone is used to reconstruct the facet complex after tumor resection. The nerve root to the tumor, typically the sensory branch, is identified and ligated with silk ties (**Figure 7**).

The sheath of the tumor is opened and the tumor removed in a piecemeal fashion. To prevent potential cerebral spinal leakage into the thoracic cavity, the area can be covered with gel foam and thrombin sealant. Once complete hemostasis is achieved, the facet and laminectomy are reconstructed using the morselized autograft bone collected in the BoneBac Press. Gross total removal of the tumor extending into the spinal canal is achieved (**Figure 8**).

The tubular retractor is removed, allowing the paraspinous muscles to return to their normal anatomic position. The fascia is closed using 2-0 interrupted Vicryl suture. A subcuticular interrupted suture is applied, and the skin incision is closed with skin glue.The patient is then repositioned in the lateral position on a sandbag to allow for adequate unilateral thoracic approach to the tumor. A thoracoscope can then be used for proper port placement. Thoracoscopic ports are placed and the De Vinci robot is positioned adequately (**Figure 9**).

Instruments are placed in the De Vinci robot for retraction of the tumor and cauterized removal of the tumor from the chest cavity. A separate port is used to place a suction to remove cautery smoke. Detaching the tumor from its spinal canal attachment allows for gross total removal and limits potential traction injury to the spinal cord. Once the tumor is resected, it can be placed into a gall bladder bag and removed via one of the thoracoscopic ports (Figure **10**).

The thoracic ports are moved, a chest tube placed, and the incisions closed in the standard fashion. Re-inflation of the lung is

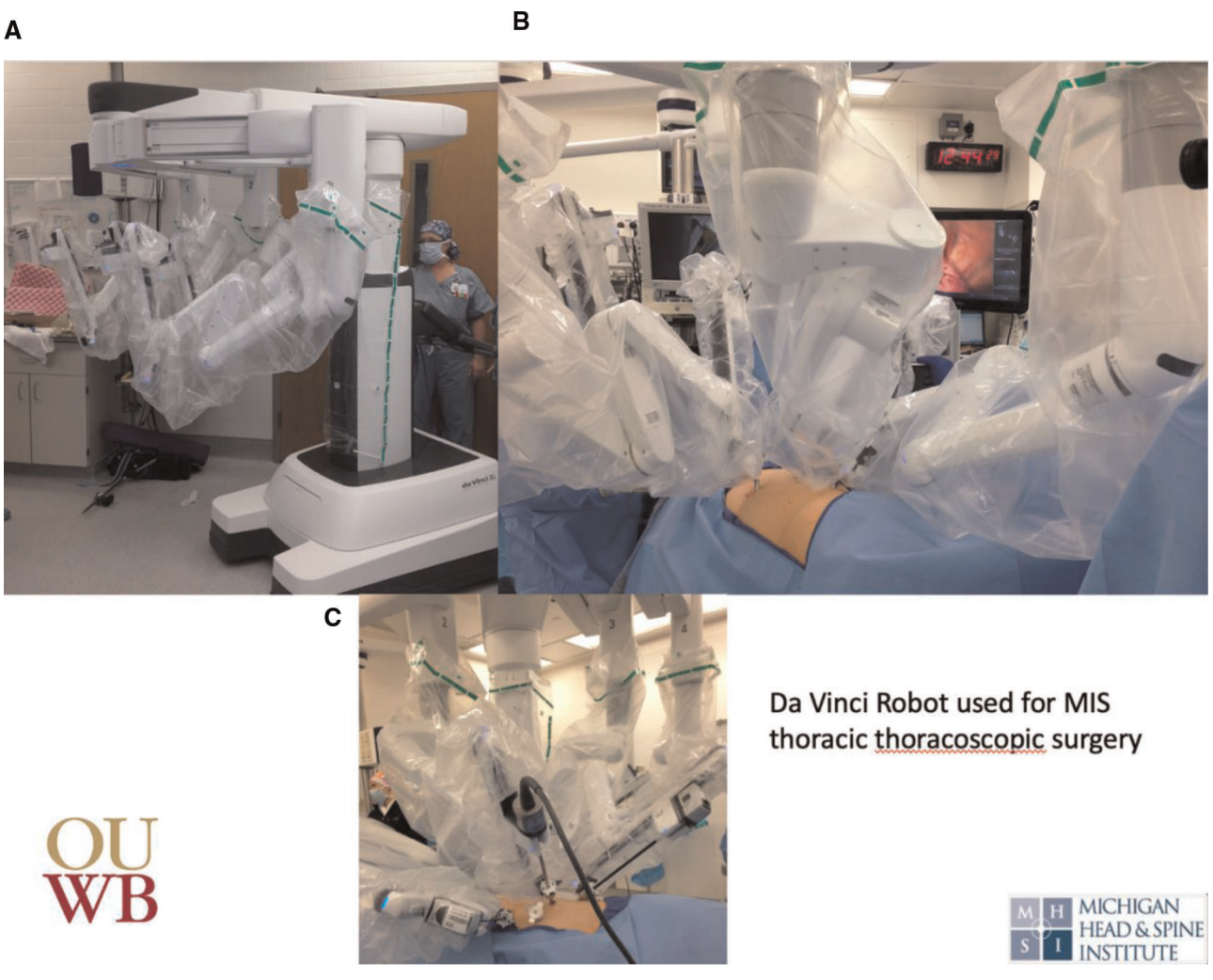

FIGURE 9 | Intra-operative photos of (**A**) da Vinci robot, (**B**) used for anterior thoracoscopic approach the spine to (**C**) removal apical thoracic tumor.

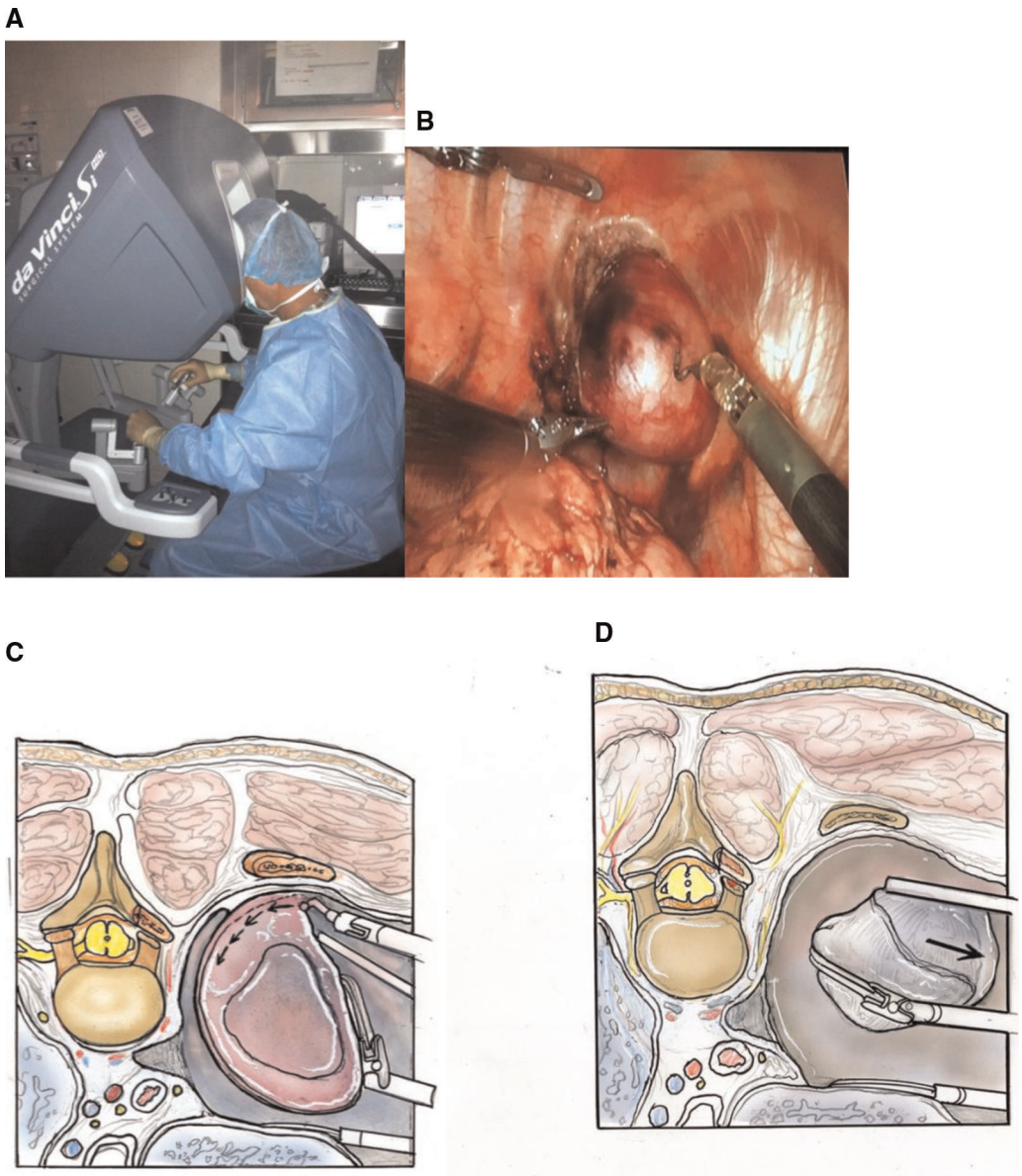

FIGURE 10 | Intra-operative photo of (**A**) surgeon using the da Vinci robot to remove (**B**) apical thoracic tumor. Illustrations showing (**C**) resection of apical thoracic tumor from the chest wall and (**D**) removal of the tumor. (Illustrations from: An Anatomical Approach to Minimally Invasive Spine Surgery, Editors; M. Perez-Cruet, R. Fessler, M. Wang, Thieme Publishing Inc. NY, 2019).

performed before final closure. Patients are typically transferred to the intensive care unit for at least an overnight stay (Figure **11**).

CONCLUSION

While there are certainly challenges when using robots in spine surgery, there is a growing interest from the surgeon's perspective to rely on robots due to the increased reproducibility, accuracy and precision. In the future, further technological advances could be integrated with robotic interaction to increase the ergonomic functionality of robotic instrumentation. Advances in artificial intelligence, big data use and haptics may all contribute to the continual improvement of robotic technology in spine surgery (33). Robotic systems such as Mazor XR, GPS Excelsius, and Rosa technologies have improved the ease and accuracy of surgical instrumentation placement. Tumors that are located in difficult positions can be resected using robotics in a minimally invasive fashion to improve outcomes and allow for more effective management of highly complex cases. MARSS or minimally- assisted robotic spine surgery represents a

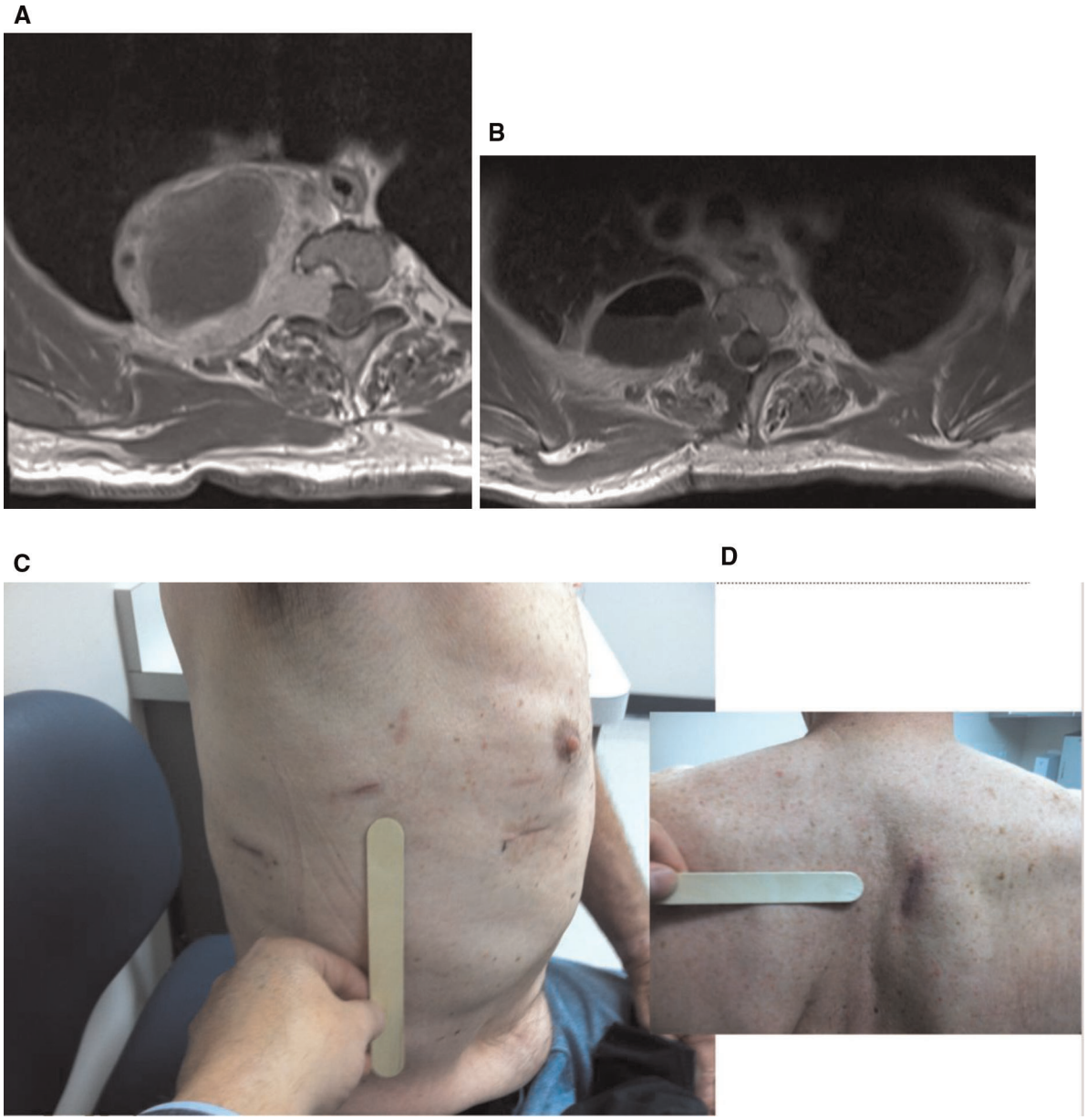

FIGURE 11 | (**A**) Pre- and (**B**) post-operative axial MRI showing gross total tumor resection. Post-operative (**C**) anterior and (**D**) posterior thoracic incision after use of the da Vinci robot to remove apical thoracic tumor.

paradigm shift in spine surgery with the potential to revolutionize the field. As technologies evolve, we will continue to see broader applications of MARSS techniques in spine surgery with the capability of improving patient outcomes.

AUTHOR CONTRIBUTIONS

All authors contributed to the article and approved the submitted version.

REFERENCES

1. Carsten S, Ringel F, Stoffel M, Reinke A, Behr M, Meyer B. Robotic technology in spine surgery: current applications and future developments. *Acta Neurochir Suppl.* (2011) 109:241–5. doi: 10.1007/978-3-211-99651-5_38
2. Booher G, Vardiman A. Navigated robotic assisted thoracic pedicle screw placement for metastatic renal cell carcinoma. *Neurosurg Focus.* (2018) 45 (VideoSuppl1):V5. doi: 10.3171/2018.7.FocusVid.18121
3. Tian W, Liu YJ, Liu B, He D, Wu JY, Han XG, et al. Guideline for thoracolumbar pedicle screw placement assisted by orthopaedic surgical robot. *Orthop Surg.* (2019) 11(2):153–9. doi: 10.1111/os.12453

4. Zhang Q, Han XG, Xu YF, Fan MX, Zhao JW, Liu YJ, et al. Robotic navigation during spine surgery. *Expert Rev Med Devices*. (2020) 17 (1):27–32. doi: 10.1080/17434440.2020.1699405
5. Li QH, Zamorano L, Pandya A, Perez R, Gong J, Diaz F. The application accuracy of the NeuroMate robot–a quantitative comparison with frameless and frame-based surgical localization systems. *Comput Aided Surg*. (2002) 7(2):90–8. doi: 10.1002/igs.10035
6. Morrell A, Morrell A, Gioia A, Freitas J, Tustumi F, Silva G, et al. The history of robotic surgery and its evolution: when illusion becomes reality. *Rev Col Bras Cir*. (2021) 48:1–9. doi: https://doi.org/10.1590/0100-6991e-20202798
7. Stüer C, Ringel F, Stoffel M, Reinke A, Behr M, Meyer B. Robotic technology in spine surgery: current applications and future developments. *Acta Neurochir Suppl*. (2011) 109:241–5. doi: 10.1007/978-3-211-99651-5_38
8. Ponnusamy I, Chewing S, Mohr C. Robotic approaches to the posterior spine. *Spine (Phila Pa 1976)*. (2009) 34(19):2104–9. doi: 10.1097/BRS.0b013e3181b20212
9. Al-Mufarrej F, Margolis M, Tempesta B, Strother E, Najam F, Gharagozloo F. From Jacobeaus to the da Vinci: thoracoscopic applications of the robot. *Surg Laparosc Endosc Percutan Tech*. (2010) 20(1):1–9. doi: 10.1097/SLE.0b013e3181cdb9e5
10. Halalmeh DR, Perez-Cruet MJ. Use of local morselized bone autograft in minimally invasive transforaminal lumbar interbody fusion: cost analysis. *World Neurosurg*. (2021) 146:e544–54. doi: 10.1016/j.wneu.2020.10.126
11. Lieberman I, Kisinde S, Hesselbacher S. Robotic-assisted pedicle screw placement during spine surgery. *JBJS Essent Surg Tech*. (2020) 10(2):e0020. doi: 10.2106/JBJS.ST.19.00020
12. Chen H, Xiao X, Chen C, Chou H, Sung C, Lin F, et al. Results of using robotic-assisted navigational system in pedicle screw placement. *PLoS One*. (2019) 14(8):e0220851. doi: 10.1371/journal.pone.0220851 eCollection 2019.
13. Liu H, Chen W, Wang Z, Lin J, Meng B, Yang H. Comparison of the accuracy between robot-assisted and conventional freehand pedicle screw placement: a systematic review and meta-analysis. *Int J Comput Assist Radiol Surg*. (2016) 11(12):2273–81. doi: 10.1007/s11548-016-1448-6
14. Buza 3rd JA, Good CR, Lehman Jr RA, Pollina J, Chua RV, Buchholz AL, et al. Robotic-assisted cortical bone trajectory (CBT) screws using the Mazor X Stealth Edition (MXSE) system: workflow and technical tips for safe and efficient use. *J Robot Surg*. (2021) 15(1):13–23. doi: 10.1007/s11701-020-01147-7
15. Fan Y, Du JP, Liu JJ, Zhang JN, Qiao HH, Liu SC, et al. Accuracy of pedicle screw placement comparing robot-assisted technology and the free hand with fluoroscopy-guided method in spine surgery: an updated meta-analysis. *Medicine (Baltimore)*. (2018) 97(22):e10970. doi: 10.1097/MD.0000000000010970
16. Ghasem A, Sharma A, Greif DN, Alam M, Al Maaieh M. The arrival of robotics in spine surgery: a review of the literature. *Spine (Phila Pa 1976)*. (2018) 43(23):1670–7. doi: 10.1097/BRS.0000000000002695
17. Momin A, Steinmetz M. Evolution of minimally invasive lumbar spine surgery. *World Neurosurg*. (2020) 140:622–6. doi: 10.1016/j.wneu.2020.05.071
18. Hussain I, Cosar M, Kirnaz S, Schmidt F, Wipplinger C, Wong T, et al. Evolving navigation, robotics, and augmented reality in minimally invasive spine surgery. *Global Spine J*. (2020) 10(2 Suppl):22S–33S. doi: 10.1177/2192568220907896
19. Kochanski R, Lombardi J, Laratta J, Lehman R, O'Toole J. Image-guided navigation and robotics in spine urgery. *Neurosurgery*. (2019) 84 (6):1179–89. doi: 10.1093/neuros/nyy630
20. Mao J, Agyei J, Khan A, Hess R, Jowdy P, Mullin J, et al. Technologic evolution of navigation and robotics in spine surgery: a historical perspective. *World Neurosurg*. (2021) 145:159–67. doi: 10.1016/j.wneu.2020.08.224
21. Bagga V, Bhattacharyya D. Robotics in neurosurgery. *Ann R Coll Surg Engl*. (2018) 100(6 sup):23–6. doi: 10.1308/rcsann.supp1.19
22. D'Souza M, Gendreau J, Keng A, Kim L, Ho A, Veeravagu A. Robotic-assisted spine surgery: history, efficacy, cost, and future trends. *Robot Surg*. (2019) 6:9–23. doi: 10.2147/RSRR.S190720
23. Naderi S, Onen MR. Robotic systems in spine surgery. *Turk Neurosurg*. (2014) 24(3):305–11. doi: 10.5137/1019-5149.JTN.8292-13.1
24. Joseph JR, Smith BW, Liu X, Park P. Current applications of robotics in spine surgery: a systematic review of the literature. *Neurosurg Focus*. (2017) 42(5): E2. doi: 10.3171/2017.2.FOCUS16544
25. Huntsman KT, Ahrendtsen LA, Riggleman JR, Ledoni CG. Robotic-assisted navigated minimally invasive pedicle screw placement in the first 100 cases at a single institution. *J Robot Surg*. (2020) 14:199–203. doi: https://doi.org/10.1007/s11701-019-00959
26. Hanna G, Kim TK, Udding SA, Ross L, Johnson JP. Video-assisted thoracoscopic image-guided spine surgery: evolution of 19 years of experience, from endoscopy to fully integrated 3D navigation. *Neurosurg Focus*. (2021) 50(1):E8. doi: 10.3171/2020.10.FOCUS20792
27. Beutler WJ, Peppelman Jr WC, DiMarco LA. The da Vinci robotic surgical assisted anterior lumbar interbody fusion: technical development and case report. *Spine (Phila Pa 1976)*. (2013) 38(4):356–63. doi: 10.1097/BRS.0b013e31826b3d72
28. Lee Z, Lee JY, Welch WC, Eun D. Technique and surgical outcomes of robot-assisted anterior lumbar interbody fusion. *J Robot Surg*. (2013) 7(2):177–85. doi: 10.1007/s11701-012-0365-0
29. Schwartz G, Sancheti M, Blasberg J. Robotic thoracic surgery. *Surg Clin North Am*. (2020) 100(2):237–48. doi: 10.1016/j.suc.2019.12.001
30. Perez-Cruet MJ, Mendoza-Torres J. Minimally invasive robotic-assisted thoracic spine surgery. In: *An anatomic approach to minimally invasive spine surgery*. 2nd ed. Thieme, Perez-Cruet MJ, Wang M, Fessler RG, eds. New York, (2019). p. 290–8. doi: 10.1055/b-005-145242
31. Hu X, Scharsschmidt TJ, Ohnmeiss DD, Lieberman IH. Robotic assisted surgeries for the treatment of spine tumors. *Int J Spine Surg*. (2015) 9:1. doi: 10.14444/2001
32. Vo CD, Jiang B, Azad T, Crawford NR, Bydon A, Theodore N. Robotic spine surgery: current state in minimally invasive surgery. *Global Spine J*. (2020) 10 (2 Suppl):34S–40S. doi: 10.1177/2192568219878131
33. Dulgeris JJ, Gonzalez-Blohm SA, Filis AK, Shea TM, Aghayev K, Vrionis FD. Robotics in neurosurgery: evolution, current challenges, and compromises. *Cancer Control*. (2015) 22(3):352–9. doi: 10.1177/107327481502200314

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A nomogram for predicting screw loosening after single-level posterior lumbar interbody fusion utilizing cortical bone trajectory screw: A minimum 2-year follow-up study

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Purpose: This study aims to investigate the risk factors for screw loosening after single-level posterior lumbar interbody fusion (PLIF) utilizing cortical bone trajectory (CBT) screw and establish a nomogram for predicting screw loosening.

Methods: A total of 79 patients (316 screws) who underwent single-level PLIF with CBT screw were included in the study. Preoperative, postoperative, and final follow-up demographic data, surgical data, and radiographic parameters were documented and analyzed to identify risk factors, and a predictive nomogram was established for screw loosening. The nomogram was assessed by concordance index (C-index), calibration plot, decision curve analysis (DCA), and internal validation.

Results: The incidence of screw loosening was 26.6% in 79 patients and 11.4% in 316 screws. Multifactorial regression analysis confirmed that fixed to S1 (FS1, OR = 3.82, 95% CI 1.12–12.71, $P = 0.029$), the coronal angle of the screw (CA, OR = 1.07, 95% CI 1.01–1.14, $P = 0.039$), and cortical bone contacted layers (CBCLs, OR = 0.17, 95% CI 0.10–0.29, $P < 0.001$) were risk factors and incorporated in the nomogram for predicting screw loosening after single-level PLIF with a CBT screw. The C-index of the nomogram was 0.877 (95% CI 0.818–0.936), which demonstrated good predictive accuracy. The calibration plot indicated an acceptable calibration of the nomogram that also had a positive benefit in guiding treatment decisions.

Conclusion: FS1, CA, and CBCLs are identified to be significant risk factors for screw loosening after single-level PLIF with the CBT technique. The nomogram we have established can be used to predict screw loosening and contribute to surgical decisions.

KEYWORDS

cortical bone trajectory, screw loosening, lumbar spine, nomogram, spine

Introduction

Cortical bone trajectory (CBT) is an alternative approach first proposed by Santoni et al. as the treatment for a lumbar degenerative disease (1). CBT screw was inserted *via* the trajectory that could engage the pars, medial, and superior cortices of the pedicle isthmus for spinal fusion, and theoretically, it provided comparable pull-out resistance and stability to a traditional pedicle screw (TPS) (2–4). Likewise, good results have been found in literature works reporting the application of CBT screw in osteoporosis lumbar spine (1, 5, 6). The main role of the screw in lumbar fusion is to reduce the motion of the spine and to conduct the stabilization, whereas screw loosening is observed in quite a few literature works (7–9). As reported, the incidence of screw loosening in TPS was 1%–60% (7, 10, 11), and risk factors were related to osteoporosis, sacrum instrument, excessive load, and local high strains; however, it was not unified. CBT screw conducts a comparable fixation to TPS according to the characteristic, and it may reduce the risk of screw loosening due to the loading resistivity of cortical bone of the pedicles. Nevertheless, the screw loosening rate was still observed to be 62.5% (9, 12–14), and the risk factors were also uncertain. This leads to consideration of the differences in risk factors for screw loosening between CBT screw and TPS.

Screw loosening in both the TPS and CBT screw may require revision surgery due to symptomatic spinal instability and instrument failure (9, 11, 15, 16); thus, comprehension of screw loosening is essential. Previous studies were researched, and we found that few studies have concentrated on CBT screw loosening, or most of them lacked long-term follow-up and sufficient evidence. Hence, clear exploration of screw loosening of CBT screws is demanded with an available analysis of the literature.

The present study aimed to detect the prevalence of screw loosening in single-level PLIF using CBT screw with a minimum of 2 years of follow-up and to establish a nomogram for predicting screw loosening individually in each vertebra.

Methods

This was a retrospective study in the institution. A total of 88 consecutive patients were included in the study from November 2017 to January 2020, and 79 eligible patients were evaluated (**Figure 1**). Inclusion criteria are listed as follows: (1) patients diagnosed with lumbar degenerative disease (lumbar disc herniation, lumbar spinal stenosis, and lumbar spondylolisthesis) and who underwent single-level PLIF with CBT screws; (2) minimum follow-up time of above 2 years. Excluded criteria are as follows: (1) incomplete radiological data; (2) patients who underwent surgery diagnosed with lumbar infection, lumbar vertebral tumor, or history of lumbar surgery. The study was approved by the institutional review board of the hospital.

Surgical technique

The patient was placed in a prone position. A 5-cm midline skin incision was performed in the lumbar area. Muscular dissection was performed until the vertebral isthmus was exposed. The facet joints were exposed, and adjacent facet joints of the fusion area were avoided. The entry point was

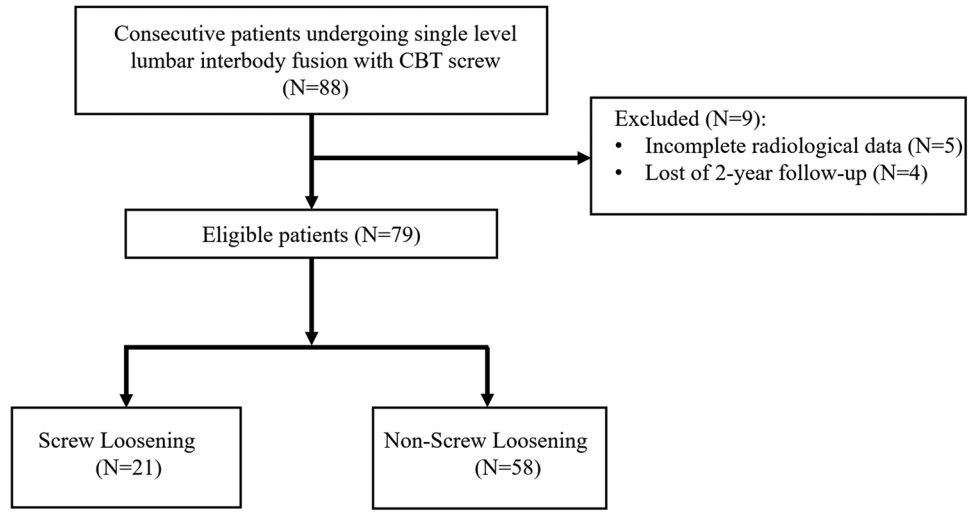

FIGURE 1
Flowchart of the study.

selected as an intersection of a vertical line through the center of the inferior facet joint of the adjacent cephalic vertebra and a horizontal line 3–4 mm below the inferior facet joint of the cephalic vertebra (a notch might be identified on the isthmus). The track was drilled with a 2 mm burr into the cortical bone with an approximate 10°–15° angle from medial to lateral and 20°–25° angle from caudal to cranial. Locating pins were placed into the track, and fluoroscopy was performed to check the position. Then, decompression was performed, and a cage (PEEK) filled with autogenous bone was implanted into the intervertebral space after endplate preparation and autogenous bone insertion. After the decompression, pins were removed, and CBT screws (for the S1 vertebra, the screw was 45 mm in length and 6.0 mm in diameter, and for other vertebras, the screw was 35 mm in length and 5.5 mm in diameter) were inserted through the tracks with spinous process preservation. Bended rods were then positioned and tightened bilaterally after compression was performed. Finally, fluoroscopy was performed to recheck the position of the screws and cage before the skin was sutured layer by layer.

Clinical and radiological evaluations

Clinical, demographic, and surgical data including age, gender, body mass index (BMI), operation time, and estimated blood loss (EBL) were collected. Radiological parameters including the coronal angle of the screw (CA), sagittal angle of the screw (SA), fixed to S1 (FS1), Hounsfield unit (HU) measurement of the trabecular bone of screw location, and cortical bone contacted layers (CBCLs) were evaluated (**Figures 2**, **3**). The HU measurement was defined as the average of three points located in the screw track in a preoperative CT scan. Screw loosening was defined as a continuous lucent zone with a size of more than 1 mm and surrounded by a thin sclerotic zone in a CT scan (7, 17, 18). Bone fusion was graded according to Bridwell classification into three grades based on a lumbar CT scan (19): Grade I, complete fusion with the bridging bone bonding with both adjacent vertebral bodies; Grade II, incomplete fusion with the bridging bone bonding with either superior or inferior vertebral bodies; Grade III, failed fusion with incomplete bony bridging. Bone fusion was assessed by CT scan slices selected from the center of the cage or the largest bone grafting (20). The Oswestry Disability Index (ODI) was used to evaluate back pain preoperatively and at a postoperative time point of 6 months and final follow-up.

Statistics analysis

SPSS Statistics Version 23.0 (IBM, Armonk, New York) and R software (version 4.1.2) were used for data analysis.

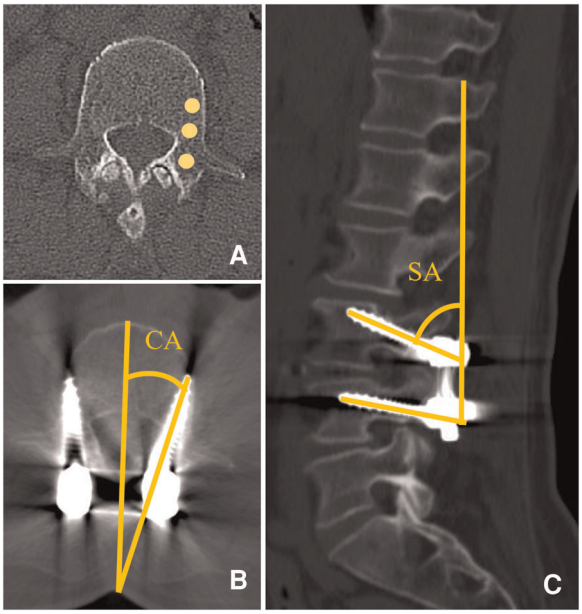

FIGURE 2
(A) HU measurement of an average of three points identified according to the screw track in the preoperative lumbar CT scan. (B) CA was defined as the angle between the screw and spinous process in the axial plane. (C) SA was defined as the angle between the screw line and vertical line in the sagittal plane.

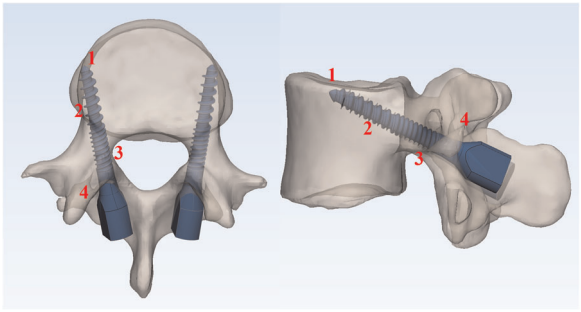

FIGURE 3
3D illustration of the maximum contact of cortical bone.

Univariate analysis was performed with an independent *t*-test and Mann–Whitney *U* test for continuous data and discontinuous data, respectively, and quantitative data were listed as means ± SD with normal distribution or as medians with interquartile ranges with non-normal distribution. The chi-squared test was used for categorical data analysis.

Multivariate logistic analysis was further performed on variates that had significant differences in univariate analysis ($P < 0.05$). In this study, CBCLs, CA, and FS1 were put into the logistic model. A multiple logistic regression model was applied to select significant variables with a stepwise forward

method, and the odds ratio (OR) and 95% confidence interval (CI) of the variables were recorded. A nomogram was established with R software. The concordance index (C-index) of the nomogram was calculated to evaluate the predictive accuracy of the nomogram utilizing the "rms" package. A calibration plot and the Hosmer–Lemeshow test were used to assess the calibration, and the nomogram was internally validated by the bootstraps of 1,000 resamples. Decision curve analysis (DCA) was calculated by the "rmda" package to evaluate the clinical usefulness of the nomogram. The reliable outcome is considered as C-index >0.75, and P value <0.05 was considered statistically significant for all data.

Results

A total of 88 consecutive patients were identified, and 79 patients (316 screws) were included in the study. The cohort contained 35 (44.3%) male patients with an average age of 65.14 ± 9.74 years, and the average BMI was 26.83 ± 4.49. The mean follow-up time was 25.38 ± 1.77 months (Table 1). The incidence of screw loosening was 26.6% (21) in the cohort and 11.4% (36) in 316 screws; 5 patients presented back pain and received conservative treatment, and the other patients (16) were asymptomatic. The patients were divided into two groups according to the presence of screw loosening: screw loosening group (SL) and no screw loosening group (non-SL). Statistically significant differences were found in CA (P = 0.039), FS1 (P = 0.029), and CBCLs (P < 0.001) between the two groups (Table 2). Multiple logistic regression was performed on these parameters, and the results demonstrated that FS1 (OR = 3.82, 95% CI 1.12–12.71, P = 0.029), CA (OR = 1.07, 95% CI 1.01–1.14, P = 0.039), and CBCLs (OR = 0.17, 95% CI 0.10–0.29, P < 0.001) were risk factors for screw loosening after single-level PLIF with CBT screws (Table 3).

The nomogram was conducted by R software (version 4.1.2) with a 0.877 (95% CI 0.818–0.936) C-index, which demonstrated good discrimination and predictive accuracy (Figure 4). Calibration evaluated by the calibration plot of the nomogram was good (Figure 5), and the Hosmer-Lemeshow test was good (P = 0.755). The internal validation by bootstraps of 1,000 resamples was excellent, with a 0.880 (95% CI 0.815–0.932) C-index. Decision curve analysis was performed, as shown in Figure 6, and when the threshold probabilities ranged from 0% to 60%, the nomogram showed a positive net benefit, which means clinical interventions implemented in those patients guided by the nomogram could obtain more benefit compared with treating all or treating none.

Application indication of the nomogram is explained in Figure 7: a 62-year-old male patient underwent single-level PLIF with CBT screws at L4/5. A postoperative CT scan showed that the CA of L4L was 5° and of at L4R was 15°. The CAs of L5L and L5R were 16° and 17°, respectively, and the CBCLs of each screw were 3, 3, 2, and 1. Thus, according to the prediction nomogram, the score of each screw was

TABLE 1 Baseline characteristics and surgical data of patients.

Factors	Total number (n = 79)	SL (n = 21)	Non-SL (n = 58)	P value
Demographics				
Age (years)	65.14 ± 9.74	64.62 ± 11.93	62.60 ± 8.87	0.420
Male, n (%)	35 (44.3)	11 (52.4)	24 (41.4)	0.385
Height (m)	1.63 ± 0.78	1.66 ± 0.08	1.62 ± 0.07	0.053
Weight (kg)	71.13 ± 13.01	74.29 ± 15.50	69.98 ± 11.94	0.196
BMI	26.83 ± 4.49	26.93 ± 4.17	26.79 ± 4.64	0.905
Follow-up time (mon)	25.38 ± 1.77	25.43 ± 1.43	25.36 ± 1.89	0.884
Surgical data				
Operation time (min)	176.54 ± 41.46	172.62 ± 43.18	177.97 ± 41.12	0.616
EBL (ml)	213.54 ± 74.13	190.00 ± 63.64	222.07 ± 76.29	0.089
Fusion grade, n (%)	-	-	-	0.267
I	29 (36.7)	10 (47.6)	19 (32.8)	-
II	42 (53.2)	8 (38.1)	34 (58.6)	-
III	8 (10.1)	3 (14.3)	5 (8.6)	-
ODI (%)				
Preoperative	49.10 ± 6.50	49.52 ± 8.68	48.95 ± 5.60	0.731
6 months	22.52 ± 4.65	23.33 ± 4.53	22.22 ± 4.70	0.353
Final follow-up	21.03 ± 4.50	21.90 ± 4.58	20.71 ± 4.47	0.299

BMI, body mass index; EBL, estimate blood loss; ODI, Oswestry disability index.

TABLE 2 Characteristics of screw-related parameters.

Factors	Total number (n = 316)	SL (n = 36)	Non-SL (n = 280)	P value
FS1, n (%)	22 (7.0)	9 (25.0)	13 (4.6)	<0.001
Hu	165.18 ± 84.08	179.04 ± 83.63	163.40 ± 83.64	0.294
SA (°)	75.97 ± 7.10	75.72 ± 8.05	76.01 ± 6.99	0.822
CA (°)	10.77 ± 5.72	13.94 ± 6.53	10.36 ± 5.49	<0.001
CBCLs (n)	4 (3–4)	2 (2–3)	4 (3–4)	<0.001

FS1, fixed to S1; SA, sagittal angle of the screw; CA, coronal angle of the screw; CBCLs, cortical bone contacted layers.

TABLE 3 Multivariable analysis of radiological parameters.

Variable	OR	95% CI	P value
FS1, n (%)	3.82	1.12–12.71	0.029
CA (°)	1.07	1.01–1.14	0.039
CBCLs (n)	0.17	0.10–0.29	<0.001

FS1, fixed to S1; CA, coronal angle of the screw; CBCLs, cortical bone contacted layers.

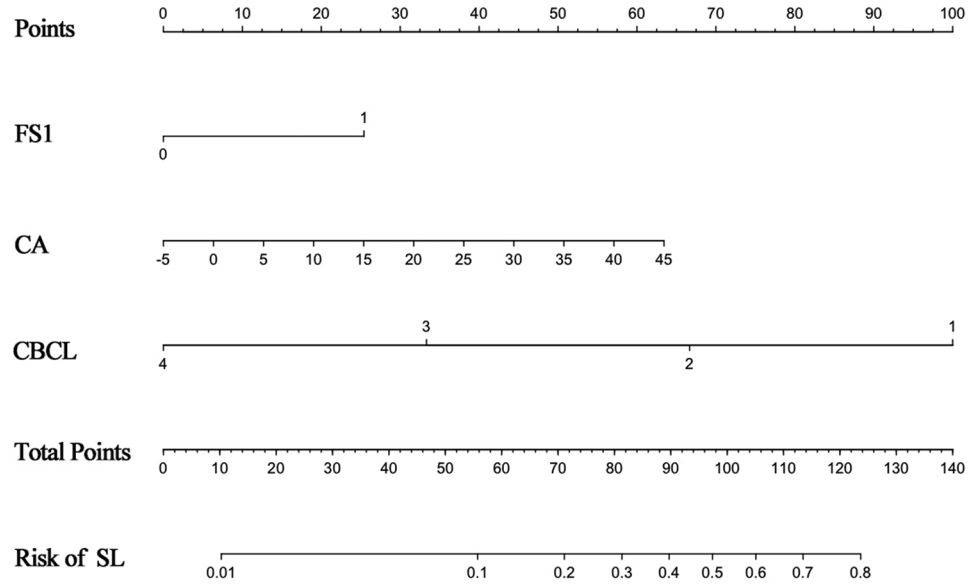

FIGURE 4
Details of the nomogram.

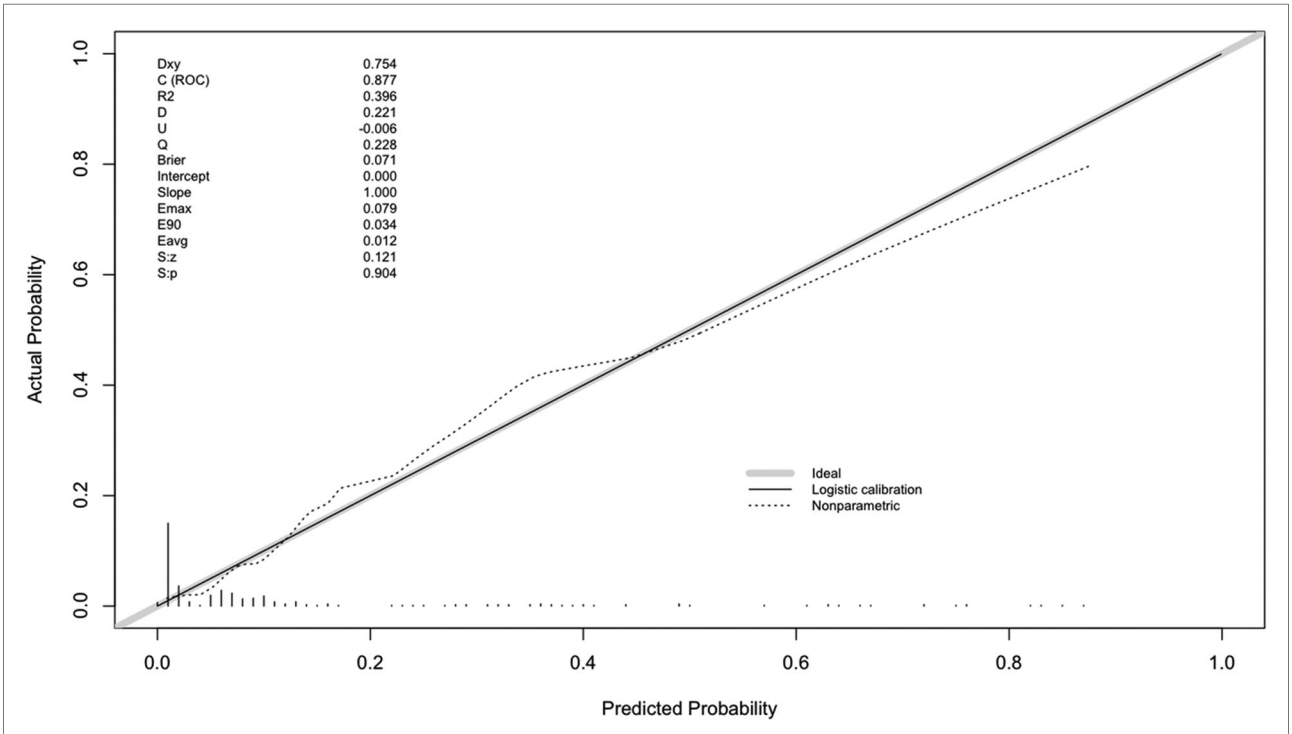

FIGURE 5
Calibration plot. The calibration of the nomogram was represented by the solid line, and any bias in the nomogram was corrected by the dashed line. The bold gray line indicates the reference line of an ideal nomogram.

approximately 45, 59, 92, and 126, which indicated that the incidence of screw loosening was <10%, 11%, 42%, and >80%. At the 1-year follow-up, we identified asymptomatic screw loosening at L4L, L5L, and L5R, which verified the accuracy of the nomogram. Also, the patient maintained asymptomatic at the final follow-up.

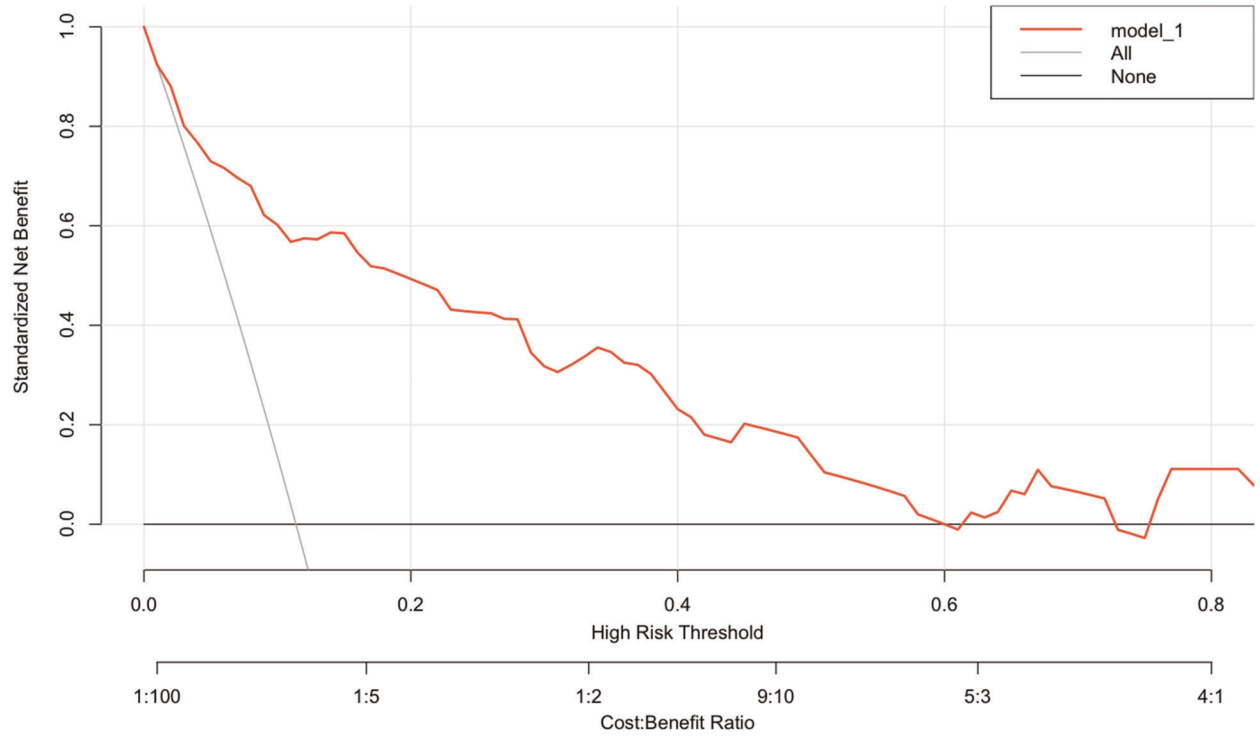

FIGURE 6
Decision curve analysis of the nomogram. The red line indicates the model. The *x*-axis and *y*-axis display the threshold probability and net benefit, respectively. The gray line represents the net benefit of treating all patients. The horizontal black line displays the net benefit of treating no patients.

To indicate whether the screw's location was in S1, three-dimensional surface plots are shown in **Figures 8A,B** to indicate the impact of CA and CBCLs on the probability of screw loosening.

Discussion

Screw loosening is common, as reported in PLIF, with an incidence of 1%–60% (7, 10, 13). Risk factors as explored are connected with osteoporosis, incorrect failing loading scenario, insufficient fusion, or screw stress distribution (7); however, most of the research studies have not reached a consensus. CBT screw has comparable pull-out resistance and stability to TPS since it was first proposed in 2009 by Santoni et al. (1). It can provide enhanced screw purchase and preferable interface strength attributed to characteristics of engaging higher density cortical bone even in osteoporosis patients (21–23). Perez-Orribo et al. explored the biomechanics of TPS and CBT and concluded that equivalent stability was found between TPS and CBT fixation (3). Matsukawa et al. found that the screw insertion torque of CBT was 1.71 times higher than that of TPS (24). Thus, theoretically, CBT screw has been proposed to promote pull-out strength and enhance the construct stability. In the present study, we found a 26.6% incidence of screw loosening in 79 samples (11.4% in 316 screws). To investigate the risk factors of screw loosening, we documented and analyzed the mentioned parameters of each screw, which would be more beneficial for surgery, and the results of risk factor analysis showed that three main factors (FS1, CA, and CBCLs) mainly constituted the predict scoring nomogram.

The odds ratio of FS1 was the highest compared to other parameters (OR = 3.82). In our study, there were 22 screws fixed in the S1 vertebra, and 9 of them (40.9%) were found to have an obvious lucent zone in the CT scan. Grigoryan et al. (25) conducted a cadaveric biomechanical study and considered that lumbosacral fixation with CBT screws was stable against loosening, which is contrary compared the results of our study. The reasons of FS1 being concluded as a risk factor of screw loosening were assessed: First, lumbosacral fixation is inherently thought to have a higher risk of screw loosening due to alignment restoration and holding strength (26–28). Second, the learning curve of lumbosacral fixation with CBT is relatively higher. Matsukawa et al. (29) elucidated that the penetrating S1 endplate CBT technique with a mean cephalad angle of 30.7° could provide favorable stability for lumbosacral fixation, while during our work, especially for

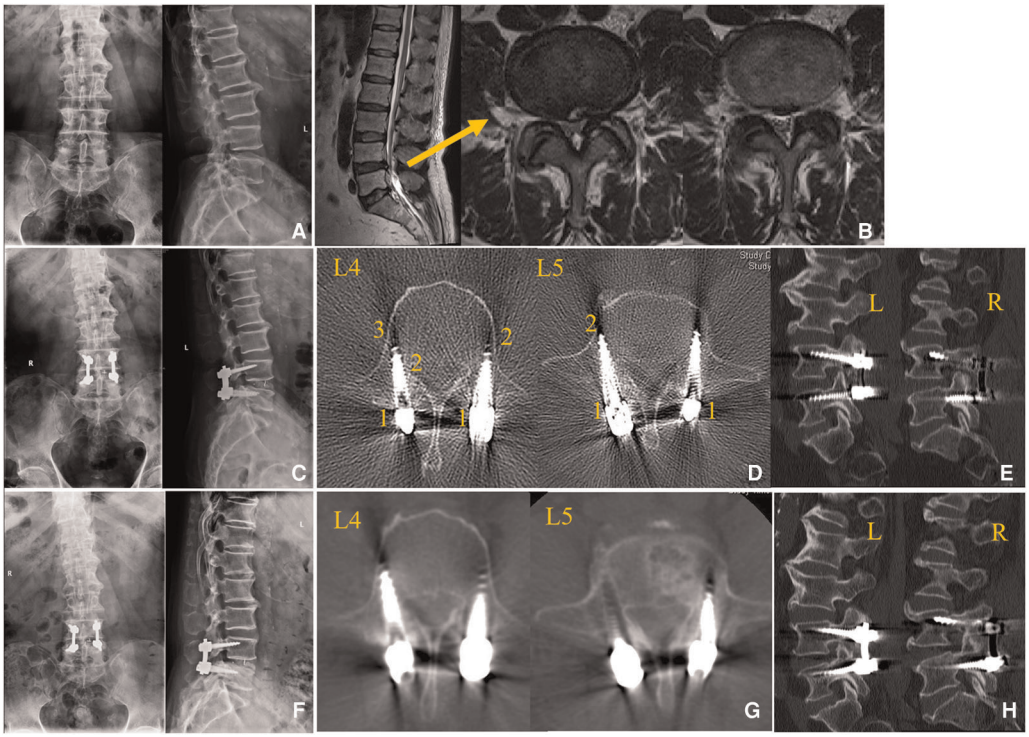

FIGURE 7
Case of the application of the nomogram. (**A**,**B**) Preoperative radiological data. (**C**–**E**) Immediate postoperative radiological data. (**F**–**H**) Radiological data at 1-year follow-up. (**A**) Lumbar spine x-ray. (**B**) Lumbar spine MRI demonstrating lumbar stenosis at L4/5. (**C**) Postoperative lumbar spine x-ray. (**D**) Postoperative lumbar spine CT scan indicating that the CBCLs of L4L, L4R, L5L, and L5R were 2, 3, 1, and 2, respectively. (**E**) Sagittal view of the lumbar spine CT scan. (**F**) After 1-year follow-up, a lumbar x-ray demonstrated a lucent zone at L4R and L5R. (**G**) Lumbar spine CT scan showing obvious screw loosening at L4L, L5L, and L5R. (**H**) Sagittal view of the lumbar spine CT scan.

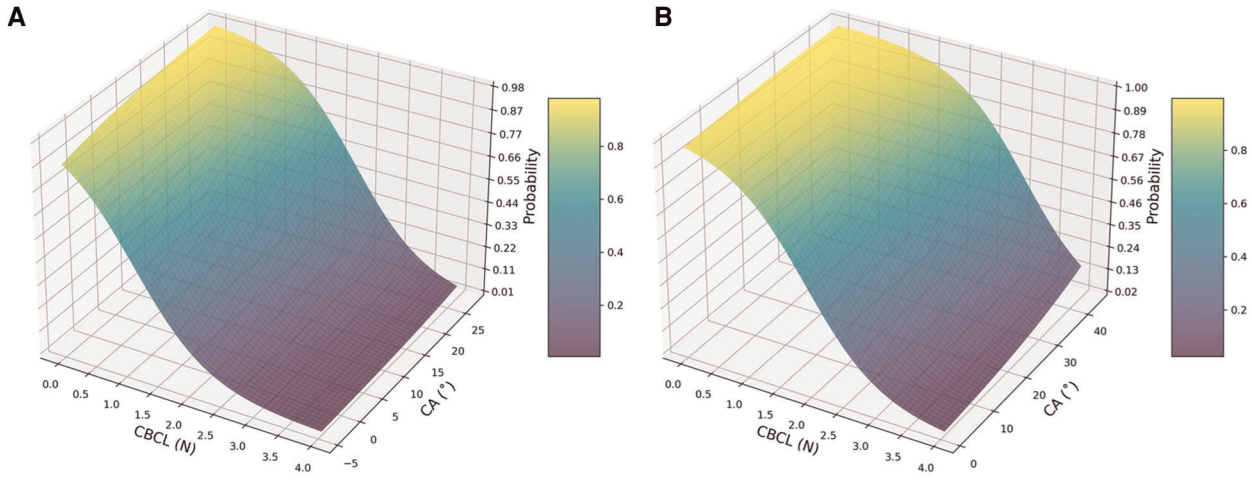

FIGURE 8
Three-dimensional surface plot demonstrating the impact of CBCL (*x*-axis) and CA (*z*-axis) on the probability of screw loosening after lumbar surgery with the CBT technique. (**A**) Probability of screw loosening when the screw was not instrumented in S1; (**B**) probability of screw loosening when the screw was instrumented in S1.

early cases, it was hard to identify a content position for the instrument in S1 and repeating screw track adjustment might result in instability, and this also occurred in other segments for early cases. Therefore, we considered that experienced surgeons are needed to perform fixation on S1; although the result was not good for FS1, we believe that CBT screw for S1 is an alternative method for fixation due to the reduction of paraspinal dissection and facility for retraction in the sacrum.

With regard to CA and CBCLs played an important role in screw loosening of CBT screw, according to the nomogram. The typical trajectory of the CBT screw contains four parts for the cortical bone to increase the stability of fixation; among these, the lateral par as the starting point is essential. The lateral par is an identifiable structure as an entry point and is less influenced by a degenerative change to provide a good bony reference in the surgery (30, 31). The starting point could also have an influence on CA. Literature works recommended an approximate 10°–14° angle to medial (32, 33), and in our study, the mean CA was 10.36° in the non-SL group and 13.94° in the SL group, which concluded similarly to the previous studies. Matsukawa (4) stated that CA was more variable than SA, and CA might have been derived from differences in the location of the starting point. We believe biochemical studies will be performed to clarify the mechanism in the future.

In the present study, we have documented and provided a reference for the measurement of SA as an angle between the screw line and vertical line because we think that this might reduce the error for measurement of wedge-shaped vertebra in some cases, while some authors recommended a method of the measurement of the angle between the screw and vertebral endplate (33, 34). However, the results showed no statistically significant difference between the two groups, but there was no denial that SA was an important parameter. Zhang et al. (35) conducted a study to compare the fixation failure between PS and CBT and concluded that different failure mechanisms underlay PS and CBT under large vertical displacement, and this may emphasize the characteristic of CBT screws in a sagittal view.

Lower BMD evaluated by dual x-ray absorptiometry (DXA) was significantly associated with screw loosening by influencing the pull-out strength (1, 36, 37); nevertheless, DXA assessed the average value of BMD. In addition to DXA, the use of HU based on a CT scan has been applied and clarified to be a reliable method for BMD evaluation (38–40), which can be used to assess the region involved by each screw. However, literature works revealed that there was no consensus on the HU value to evaluate a low BMD as a risk for osteoporosis. In the current study, BMD around the screw was assessed by the HU value to explore whether BMD would be a risk factor for screw loosening, and the result was negative. This demonstrated that the BMD of the region where screw threaded could not make much difference. Lee et al. (33) reported the HU measurement of cortical bone; however, we have attempted to make the repetition and the results showed poor inter-rater reproducibility due to the thin wall of cortical bone, and we did not adopt the method to replace CBCLs.

The study had some limitations, mainly due to retrospective analysis with small sample size. The surgery with the CBT technique was performed during the learning curve of the early period, and this might contribute to the loosening of the S1 screw. Our study focused on the local view of screws to explore the potential factors of screw loosening; however, we did not include parameters related to fusion because it was hard to judge whether the fusion failure was caused by screw loosening or bone graft. Further studies with experienced surgical techniques will be performed to validate the present study.

Conclusion

The CBT technique offers an alternative method for lumbar surgery with TPS. Although CBT screws provide good stability for fixation, we have identified significant risk factors for screw loosening. A perioperative evaluation with the nomogram can provide a reliable prediction of screw loosening with CBT screws and contribute to surgical decisions to avoid complications.

Data availability statement

The datasets used and/or analyzed during the current study are not publicly available due to the data being confidential; however, they are available from the corresponding author on a reasonable request.

Ethics statement

The studies involving human participants were reviewed and approved by the Institutional Review Board of Beijing Chao-yang Hospital. The patients/participants provided their written informed consent to participate in this study.

Author contributions

YZ writing—review and editing, formal analysis, collection and analysis of the data, and study design. YL formal analysis, collection and analysis of the data, and study design. YH performed the surgeries and designed and supervised the study. LG performed the surgeries. XZ collected and analyzed the data and methodology. AP validation, methodology, and investigation. HL collected and analyzed the data and

validation. BW collected and analyzed the data. YuzL performed the surgeries and designed and supervised the study. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

1. Santoni BG, Hynes RA, McGilvray KC, Rodriguez-Canessa G, Lyons AS, Henson MA, et al. Cortical bone trajectory for lumbar pedicle screws. *Spine J.* (2009) 9(5):366–73. doi: 10.1016/j.spinee.2008.07.008

2. Akpolat YT, İnceoğlu S, Kinne N, Hunt D, Cheng WK. Fatigue performance of cortical bone trajectory screw compared with standard trajectory pedicle screw. *Spine (Phila Pa 1976).* (2016) 41(6):E335–41. doi: 10.1097/BRS.0000000000001233

3. Perez-Orribo L, Kalb S, Reyes PM, Chang SW, Crawford NR. Biomechanics of lumbar cortical screw-rod fixation versus pedicle screw-rod fixation with and without interbody support. *Spine (Phila Pa 1976).* (2013) 38(8):635–41. doi: 10.1097/BRS.0b013e318279a95e

4. Matsukawa K, Yato Y. Lumbar pedicle screw fixation with cortical bone trajectory: a review from anatomical and biomechanical standpoints. *Spine Surg Relat Res.* (2017) 1(4):164–73. doi: 10.22603/ssrr.1.2017-0006

5. Shi W, Aierken G, Wang S, Abuduwali N, Xia Y, Rezhake R, et al. Application study of three-dimensional printed navigation template between traditional and novel cortical bone trajectory on osteoporosis lumbar spine. *J Clin Neurosci.* (2021) 85:41–8. doi: 10.1016/j.jocn.2020.11.038

6. Rexiti P, Aierken G, Wang S, Abudurexiti T, Abuduwali N, Deng Q, et al. Anatomical research on strength of screw track fixation in novel cortical bone trajectory for osteoporosis lumbar spine. *Am J Transl Res.* (2019) 11(11):6850–9.

7. Galbusera F, Volkheimer D, Reitmaier S, Berger-Roscher N, Kienle A, Wilke HJ. Pedicle screw loosening: a clinically relevant complication? *Eur Spine J.* (2015) 24(5):1005–16. doi: 10.1007/s00586-015-3768-6

8. Huang Y, Wang J. Mechanism of and factors associated with the loosening of the implant abutment screw: a review. *J Esthet Restor Dent.* (2019) 31(4):338–45. doi: 10.1111/jerd.12494

9. Chen CH, Chen DC, Huang HM, Chuang HY, Hsu WL, Cho DY, et al. Level-based analysis of screw loosening with cortical bone trajectory screws in patients with lumbar degenerative disease. *Medicine (Baltimore).* (2020) 99(40):e22186. doi: 10.1097/MD.0000000000022186

10. Marie-Hardy L, Pascal-Moussellard H, Barnaba A, Bonaccorsi R, Scemama C. Screw loosening in posterior spine fusion: prevalence and risk factors. *Global Spine J.* (2020) 10(5):598–602. doi: 10.1177/2192568219864341

11. Yuan L, Zhang X, Zeng Y, Chen Z, Li W. Incidence, risk, and outcome of pedicle screw loosening in degenerative lumbar scoliosis patients undergoing long-segment fusion. *Global Spine J.* (2021) 5:21925682211017477. doi: 10.1177/21925682211017477

12. Hoffman H, Verhave B, Jalal MS, Beutler T, Galgano MA, Chin LS. Comparison of cortical bone trajectory screw placement using the midline lumbar fusion technique to traditional pedicle screws: a case-control study. *Int J Spine Surg.* (2019) 13(1):33–8. doi: 10.14444/6005

13. Chen CH, Tu CH, Chen DC, Huang HM, Chuang HY, Cho DY, et al. Incidence of screw loosening in cortical bone trajectory fixation technique between single- and dual-threaded screws. *Medicines (Basel, Switzerland).* (2021) 8(9):1–8. doi: 10.3390/medicines8090050

14. Liu L, Zhang S, Liu G, Yang B, Wu X. Early clinical outcome of lumbar spinal fixation with cortical bone trajectory pedicle screws in patients with osteoporosis with degenerative disease. *Orthopedics.* (2019) 42(5):e465–e71. doi: 10.3928/01477447-20190604-01

15. Wu JC, Huang WC, Tsai HW, Ko CC, Wu CL, Tu TH, et al. Pedicle screw loosening in dynamic stabilization: incidence, risk, and outcome in 126 patients. *Neurosurg Focus.* (2011) 31(4):E9. doi: 10.3171/2011.7.FOCUS11125

16. McAfee PC, Weiland DJ, Carlow JJ. Survivorship analysis of pedicle spinal instrumentation. *Spine (Phila Pa 1976).* (1991) 16(8 Suppl):S422–7.

17. Pihlajämaki H, Myllynen P, Böstman O. Complications of transpedicular lumbosacral fixation for non-traumatic disorders. *J Bone Joint Surg Br Vol.* (1997) 79(2):183–9. doi: 10.1302/0301-620X.79B2.0790183

18. Ohlin A, Karlsson M, Düppe H, Hasserius R, Redlund-Johnell I. Complications after transpedicular stabilization of the spine. A survivorship analysis of 163 cases. *Spine (Phila Pa 1976).* (1994) 19(24):2774–9. doi: 10.1097/00007632-199412150-00007

19. Bridwell KH, Lenke LG, McEnery KW, Baldus C, Blanke K. Anterior fresh frozen structural allografts in the thoracic and lumbar spine. Do they work if combined with posterior fusion and instrumentation in adult patients with kyphosis or anterior column defects? *Spine (Phila Pa 1976).* (1995) 20 (12):1410–8. doi: 10.1097/00007632-199506020-00014

20. Hasegawa T, Ushirozako H, Shigeto E, Ohba T, Oba H, Mukaiyama K, et al. The titanium-coated PEEK cage maintains better bone fusion with the endplate than the PEEK cage 6 months after PLIF surgery: a multicenter, prospective, randomized study. *Spine (Phila Pa 1976).* (2020) 45(15):E892–e902. doi: 10.1097/BRS.0000000000003464

21. Li B, Jiang B, Fu Z, Zhang D, Wang T. Accurate determination of isthmus of lumbar pedicle: a morphometric study using reformatted computed tomographic images. *Spine (Phila Pa 1976).* (2004) 29(21):2438–44. doi: 10.1097/01.brs.0000144355.50660.65

22. Mai HT, Mitchell SM, Hashmi SZ, Jenkins TJ, Patel AA, Hsu WK. Differences in bone mineral density of fixation points between lumbar cortical and traditional pedicle screws. *Spine J.* (2016) 16(7):835–41. doi: 10.1016/j.spinee.2015.11.034

23. Li HM, Zhang RJ, Gao H, Jia CY, Xing T, Zhang JX, et al. Biomechanical fixation properties of the cortical bone trajectory in the osteoporotic lumbar spine. *World Neurosurg.* (2018) 119:e717–e27. doi: 10.1016/j.wneu.2018.07.253

24. Matsukawa K, Yato Y, Kato T, Imabayashi H, Asazuma T, Nemoto K. In vivo analysis of insertional torque during pedicle screwing using cortical bone trajectory technique. *Spine (Phila Pa 1976).* (2014) 39(4):E240–5. doi: 10.1097/BRS.0000000000000116

25. Grigoryan G, Inceoglu S, Danisa OA, Cheng W. Sacral endplate penetrating screw for lumbosacral fixation: a cadaveric biomechanical study. *Oper Neurosurg (Hagerstown).* (2019) 17(4):396–402. doi: 10.1093/ons/opy388

26. Nakashima H, Kanemura T, Satake K, Ito K, Ishikawa Y, Ouchida J, et al. The prevalence and risk factors for S2 alar-iliac screw loosening with a minimum 2-year follow-up. *Asian Spine J.* (2020) 14(2):177–84. doi: 10.31616/asj.2019.0127

27. Guo HZ, Tang YC, Guo DQ, Ma YH, Yuan K, Li YX, et al. Pedicle screw fixation in single-level, double-level, or multilevel posterior lumbar fusion for osteoporotic spine: a retrospective study with a minimum 2-year follow-up. *World Neurosurg.* (2020) 140:e121–e8. doi: 10.1016/j.wneu.2020.04.198

28. Banno T, Hasegawa T, Yamato Y, Kobayashi S, Togawa D, Oe S, et al. Prevalence and risk factors of iliac screw loosening after adult spinal deformity surgery. *Spine (Phila Pa 1976).* (2017) 42(17):E1024–e30. doi: 10.1097/BRS.0000000000002047

29. Matsukawa K, Yato Y, Kato T, Imabayashi H, Asazuma T, Nemoto K. Cortical bone trajectory for lumbosacral fixation: penetrating S-1 endplate screw technique: technical note. *J Neurosurg Spine.* (2014) 21(2):203–9. doi: 10.3171/2014.3.SPINE13665

30. Su BW, Kim PD, Cha TD, Lee J, April EW, Weidenbaum M, et al. An anatomical study of the mid-lateral pars relative to the pedicle footprint in the lower lumbar spine. *Spine (Phila Pa 1976)*. (2009) 34(13):1355–62. doi: 10.1097/BRS.0b013e3181a4f3a9

31. Iwatsuki K, Yoshimine T, Ohnishi Y, Ninomiya K, Ohkawa T. Isthmus-guided cortical bone trajectory for pedicle screw insertion. *Orthop Surg*. (2014) 6(3):244–8. doi: 10.1111/os.12122

32. Kaye ID, Prasad SK, Vaccaro AR, Hilibrand AS. The cortical bone trajectory for pedicle screw insertion. *JBJS Rev*. (2017) 5(8):e13. doi: 10.2106/JBJS.RVW.16.00120

33. Lee CK, Kim D, An SB, Shin DA, Ha Y, Kim KN, et al. An optimal cortical bone trajectory technique to prevent early surgical complications. *Br J Neurosurg*. (2020) 9:1–7. doi: 10.1080/02688697.2020.1821172

34. Matsukawa K, Yato Y, Nemoto O, Imabayashi H, Asazuma T, Nemoto K. Morphometric measurement of cortical bone trajectory for lumbar pedicle screw insertion using computed tomography. *J Spinal Disord Tech*. (2013) 26(6):E248–53. doi: 10.1097/BSD.0b013e318288ac39

35. Zhang T, Ren X, Feng X, Diwan A, Luk KDK, Lu WW, et al. Failure mechanisms of pedicle screws and cortical screws fixation under large displacement: a biomechanical and microstructural study based on a clinical case scenario. *J Mech Behav Biomed Mater*. (2020) 104:103646. doi: 10.1016/j.jmbbm.2020.103646

36. Matsukawa K, Taguchi E, Yato Y, Imabayashi H, Hosogane N, Asazuma T, et al. Evaluation of the fixation strength of pedicle screws using cortical bone trajectory: what is the ideal trajectory for optimal fixation? *Spine (Phila Pa 1976)*. (2015) 40(15):E873–8. doi: 10.1097/BRS.0000000000000983

37. Löffler MT, Sollmann N, Burian E, Bayat A, Aftahy K, Baum T, et al. Opportunistic osteoporosis screening reveals low bone density in patients with screw loosening after lumbar semi-rigid instrumentation: a case-control study. *Front Endocrinol (Lausanne)*. (2020) 11:552719. doi: 10.3389/fendo.2020.552719

38. Pickhardt PJ, Pooler BD, Lauder T, del Rio AM, Bruce RJ, Binkley N. Opportunistic screening for osteoporosis using abdominal computed tomography scans obtained for other indications. *Ann Intern Med*. (2013) 158(8):588–95. doi: 10.7326/0003-4819-158-8-201304160-00003

39. Zaidi Q, Danisa OA, Cheng W. Measurement techniques and utility of hounsfield unit values for assessment of bone quality prior to spinal instrumentation: a review of current literature. *Spine (Phila Pa 1976)*. (2019) 44(4):E239–e44. doi: 10.1097/BRS.0000000000002813

40. Zou D, Li W, Deng C, Du G, Xu N. The use of CT hounsfield unit values to identify the undiagnosed spinal osteoporosis in patients with lumbar degenerative diseases. *Eur Spine J*. (2019) 28(8):1758–66. doi: 10.1007/s00586-018-5776-9

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One step excision combined with unilateral transforaminal intervertebral fusion *via* minimally invasive technique in the surgical treatment of spinal dumbbell-shaped tumors: A retrospective study with a minimum of 5 years' follow-up

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Introduction: Spinal dumbbell-shaped tumors are rare, usually benign tumors with intraspinal and paravertebral components connected through intervertebral foramen. Complete excision is often performed through traditional open surgery (TOS). The efficacy and long-term outcomes of minimally invasive surgery (MIS) have not been reported to date in resection of dumbbell-shaped spinal tumors.

Purpose: The purpose was to evaluate the efficacy and long-term outcomes of minimally invasive resection combined with unilateral transforaminal intervertebral fusion (TIF) through comparing with TOS in the treatment of spinal dumbbell-shaped tumors.

Methods: Fifteen patients underwent MIS and 18 patients underwent TOS. Thoracic dumbbell-shaped tumors were directly exposed after removal of costotransverse joints, adjacent rib components, unilateral hemilamina, and facet joints. Lumbar dumbbell-shaped tumors were completely exposed after removal of transverse processes, unilateral hemilamina, and facet joints. Whether for minimally invasive resection or traditional open removal, dumbbell-shaped tumors were completely excised and unilateral TIF was performed to guarantee spinal stability. All patients were followed up for 5 years at least.

Results: The mean length of surgical incision for two groups was 3.47 ± 0.37 vs. 6.49 ± 0.39 cm ($p < 0.05$). The average duration of the operation was 131.67 ± 26.90 vs. 144.17 ± 23.59 min ($p > 0.05$). The mean blood loss was 172.00 ± 48.79 vs. 285.83 ± 99.31 ml ($p < 0.05$). No blood transfusions were required in the two groups. The median length of hospitalization was 6 vs. 10 days (range: 5–8 vs. 7–14 days). The patients of two groups were monitored for an average of 65.93 ± 3.88 vs. 65.78 ± 3.56 months. At 5-year follow-up, all patients presented with normal neurological function (American Spinal Injury Association scale E). The Oswestry Disability Index in the MIS group decreased

significantly more than the TOS group. No spondylolisthesis or spinal instability were found in the follow-up period. There was no recurrence of any spinal tumor 5 years after surgery. **Conclusions:** Spinal dumbbell-shaped tumors can be safely and effectively treated with minimally invasive resection combined with unilateral TIF. Compared with TOS, MIS offers a reduced length of surgical incision, blood loss, hospital stay, and postoperative pain. This surgical protocol might provide an alternative for the treatment of spinal dumbbell-shaped tumors.

KEYWORDS

dumbbell-shaped tumors, minimally invasive technique, one step, unilateral transforaminal intervertebral fusion, traditional open surgery

Introduction

Spinal dumbbell-shaped tumors are rare lesions located inside and outside the dura or spinal canal. As the tumor portions are connected through the intervertebral foramen, the tumors resemble a dumbbell. The most common types of spinal dumbbell-shaped tumors are derived from the spinal nerve sheath. These include schwannomas, neurofibromas, and neurilemmomas (1, 2). Although majority are benign, they usually compress the nerve root and spinal cord and result in progressive pain or neurological deficits. Spinal dumbbell-shaped tumors most often occur in the cervical and thoracic regions, and lumbar tumors are relatively rare.

The treatment for spinal dumbbell-shaped tumors is gross total resection (GTR), which can alleviate clinical symptoms and relieve compression on neural structures. Traditionally, spinal tumors are surgically resected through open approaches such as posterior, posterolateral, combined posterior, and anterior approaches. Open surgical excision requires a large amount of paraspinal muscle displacement from bony components to clearly expose the tumors. These procedures are associated with significant potential complications (3). Recently, emphasis has been placed on minimally invasive techniques to reduce paraspinal tissue disruption and enhance recovery after surgery, while achieving the same clinical outcomes.

Minimally invasive techniques have been extensively used in a variety of spinal pathologies for decades. Compared with open procedures, minimally invasive techniques have been shown to minimize muscle and soft tissue dissection, decrease blood loss, decrease hospitalization costs, shorten hospital stay, and improve recovery time (4–6). Biomechanically, minimally invasive techniques also lead to less spinal destabilization than open surgeries (7, 8). Based on these advantages, minimally invasive techniques have been introduced to treat spinal tumors (9). In a previous paper, we reported two cases of thoracic dumbbell-shaped tumors treated with minimally invasive techniques (10).

To date, reports of treatment of spinal dumbbell-shaped tumors with minimally invasive techniques have been limited to case reports or small series (11, 12). The mid-term or long-term outcomes of minimally invasive resection through the paraspinal muscle approach combined with unilateral transforaminal intervertebral fusion (TIF) have rarely been reported following treatment of spinal dumbbell-shaped tumors. This study aimed to evaluate the efficacy and long-term outcomes of this minimally invasive technique by comparing with traditional open surgery (TOS) in resections of dumbbell-shaped spinal tumors.

Patients and methods

Patients

Approval for this study was obtained from the Medical Ethics Committee of Zhongshan Hospital. Before the procedure, informed consent was acquired from the patients. Between December 2013 and January 2015, patients who were diagnosed with spinal dumbbell-shaped tumors and underwent surgical resection combined with unilateral TIF were enrolled. The patients treated with minimally invasive surgery (MIS) were assigned to group 1. The patients treated with TOS were assigned to group 2. The localization of the dumbbell-shaped tumors and the distinction between benign and malignant tumors were determined by magnetic resonance imaging (MRI) scans.

Surgical technique

All surgical manipulations were performed by the same senior surgeon (YG), who has over 25 years of experience in spine surgery. After being anesthetized, endotracheally intubated, and mechanically ventilated, the patient was turned prone on a radiolucent operating table. The correct area of the affected vertebrae was identified using anteroposterior and lateral fluoroscopy and Kirschner wires. The posterior surgical area was conventionally sterilized and draped. Preoperative computed tomography (CT) was

performed to evaluate the pedicles of adjacent vertebrae and to determine the optimal entry angle and depth in the coronal and sagittal planes.

When the pedicles of superior and inferior vertebrae adjacent to tumor were intact (**Figures 1B1, B2**), the tumor was completely resected from the lesion side, and unilateral TIF was performed on the ipsilateral side. For these patients, a paramedian mini incision was made 2 cm from the midline to access the dumbbell-shaped tumor and to insert the pedicle screws and cage. When the pedicles of superior and inferior vertebrae adjacent to tumor were damaged (**Figure 2**), the tumor was completely resected and the cage was inserted from the lesion side; unilateral pedicle screws fixation was performed on the contralateral side through a standard posterior midline incision about 35-mm and bilateral paraspinal muscle-splitting approaches.

Blunt finger dissection between multifidus and longissimus muscles was performed to expose vertebral facet joints and transverse processes of the superior and inferior vertebrae. The pedicle screws were placed on the junction between the lateral facet wall and the superior third of the occurred transverse process. The cortical bone at the entry site to pedicle was decorticated and either a pedicle probe or a handheld curette was used to enter the pedicle. The continuity of the pedicle wall was confirmed using a small ball-tipped probe to ensure that there was no violation of the spinal canal or neuroforamen. The pedicle screws were implanted into the vertebral body, and anteroposterior and

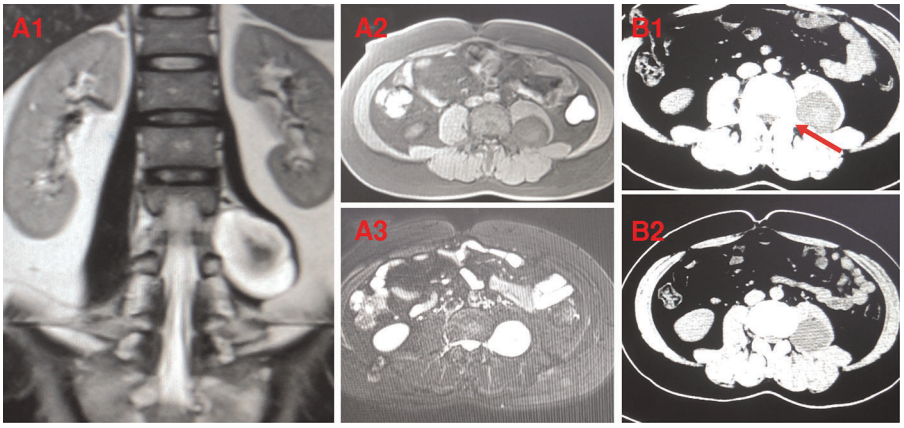

FIGURE 1
Preoperative MRI and CT showed lumbar dumbbell-shaped tumor of a 34-year-old male patient (case 5) (**A**,**B**). (**A1**) coronal MRI; (**A2**, **A3**) axial MRI; (**B1**, **B2**) axial CT. The pedicles of adjacent vertebra to lumbar dumbbell-shaped tumor (L3/L4) were intact. The red arrow indicates intact pedicle.

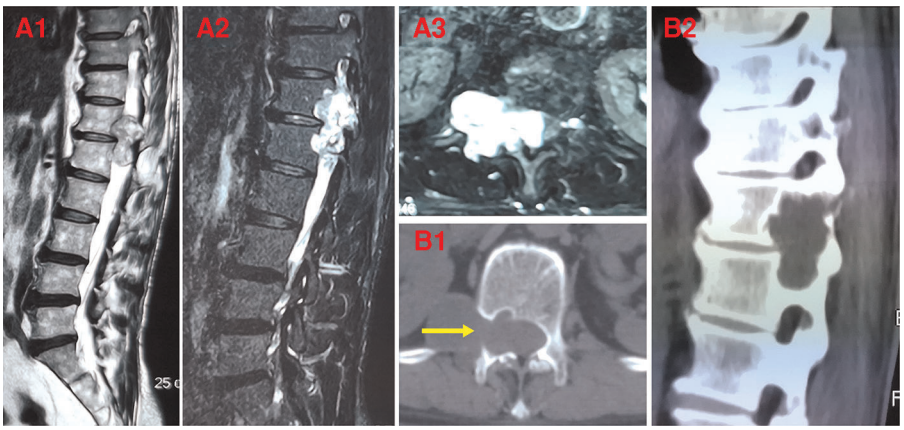

FIGURE 2
Preoperative MRI and CT showed thoracic dumbbell-shaped tumor of a 58-year-old male patient (case 15) (**A**,**B**). (**A1**, **A2**) sagittal MRI; (**A3**) axial MRI; (**B1**) axial CT; (**B2**) sagittal CT. The pedicles of adjacent vertebra to thoracic dumbbell-shaped tumor (T12/L1) were involved and damaged. The yellow arrow indicates the damaged pedicle.

lateral fluoroscopy was performed to confirm the position of pedicle screws (Figures 3A1, A2).

Serial dilators were then used to create a muscle-splitting surgical channel into the target tumor area. An expandable tubular retractor was passed over the dilators to center over the tumor, and the retractor was fixed with a flexible arm to the operating table (Figure 3B). To completely expose the intraspinal component of dumbbell tumor, unilateral hemilaminectomy and total facetectomy were performed in piecemeal fashion using osteotomes and rongeurs. To completely expose the paravertebral component of dumbbell tumor, the costotransverse joints and adjacent ribs were removed for thoracic tumors while the transverse processes were removed for lumbar tumors. Then, the intercostal muscle or the intertransverse fascia was opened to access the tumor capsule. The paravertebral part of tumor could be separated from the thoracic pleura or iliopsoas muscle and completely pulled out using fingers if the tumor was easily mobilized (Figure 3C); otherwise, piecemeal excision of tumor was performed (Figures 4C1, C2). The nerve root

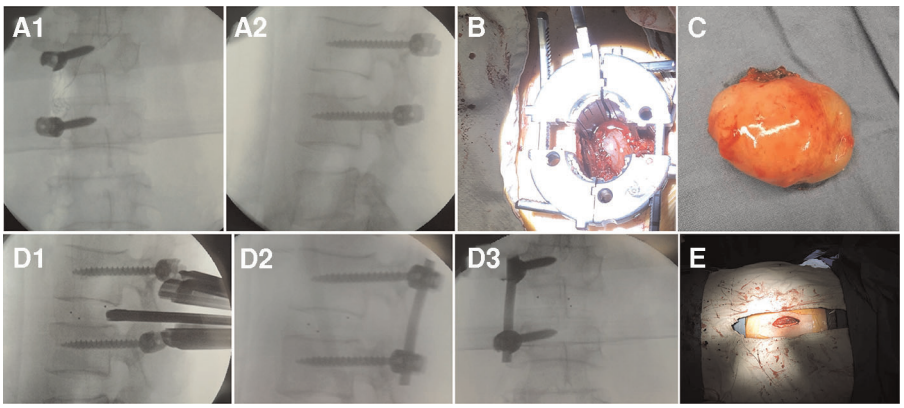

FIGURE 3
One-step excision combined with unilateral TIF *via* minimally invasive technique was performed to treat lumbar dumbbell-shaped tumors in case 5 as follows: (**A1**, **A2**) The pedicle screws were implanted into the vertebral body. (**B**) The dumbbell-shaped tumor was exposed through the expandable tubular retractor. (**C**) The dumbbell-shaped tumor was completely separated from iliopsoas muscle and excised in one step. (**D1**) The interbody cage was placed into the intervertebral interspace. (**D2**, **D3**) The rod was placed and fixed with two pedicle screws. (**E**) The paramedian mini incision was made 2 cm from the midline.

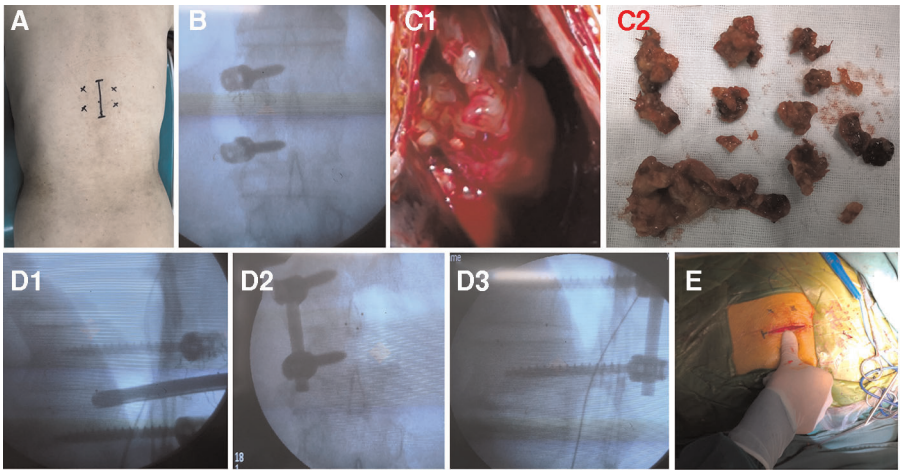

FIGURE 4
One-step excision combined with unilateral TIF *via* the minimally invasive technique was performed to treat thoracic dumbbell-shaped tumors with damaged adjacent pedicles in case 15 as follows: (**A**) the standard posterior midline incision about 35 mm and bilateral paraspinal muscle-splitting approaches were performed to place unilateral pedicle screws on the contralateral side and insert cage from the lesion side after the removal of dumbbell tumor. (**B**) The pedicle screws were implanted into the vertebral body. (**C1**, **C2**) The border of tumor is not clear and the tumor was excised in piecemeal fashion little by little. (**D1**) The interbody cage was placed in the intervertebral interspace. (**D2**, **D3**) The rod was placed and fixed with two pedicle screws. (**E**) The standard posterior mini incision was made from the midline.

involved was protected. After tumor resection, a standard ipsilateral discectomy was performed through the tubular retractor. The disc material and cartilaginous endplate were totally removed with the disc forceps and endplate scrapers. The interbody cage was filled with autograft bone and was placed into the intervertebral space (**Figure 3D1**). A rod was then placed and fixed with two pedicle screws after removal of the expandable retractor (**Figures 3D2, D3**). The wound was thoroughly irrigated, and a suction drain was inserted. For thoracic tumors, the thoracic pleura tears should be repaired, and placement of a chest tube was necessary depending on the hydrothorax or pneumothorax. The fascia was closed using absorbable sutures and the wound was closed in layers (**Figure 3E**).

No external braces were used after the operation. The patients were mobilized as soon as possible after surgery. After discharge, the patients were encouraged to resume their daily routines and were monitored as outpatients in the hospital ward.

Clinical follow-up

All patients were assessed in terms of clinical outcomes on admission, after surgery, and at 3 months, 1 year, 2 years, and 5 years postoperatively. The pain intensity was assessed using a visual analog scale (VAS), and the motor/sensory outcomes were evaluated according to the American Spinal Injury Association (ASIA) scale. The Oswestry Disability Index (ODI) was performed preoperatively and 2 and 5 years after surgery. The length of surgical incision, intraoperative blood loss, operative time, and duration of hospitalization were analyzed. Spinal MRI scanning was performed before and after the operation to confirm the complete resection of tumor. X-ray and CT were performed on admission, after surgery, and 3 months, 1 year, 2 years, and 5 years after surgery. The fusion status was assessed according to the Bridwell posterior fusion grades (13). At the final follow-up, MRI was used in all patients to check if there was the recurrence of spinal tumor 5 years after surgery.

Statistical analysis

All continuous variables were recorded and statistically analyzed by SPSS software (SPSS Inc., Chicago, IL). Values were expressed as mean ± SD. The level of significance was set at a p-value of ≤ 0.05.

Results

Fifteen patients underwent minimally invasive resection and 18 underwent traditional open surgery. All tumors were radiographically benign. The tumors were located in the extradural region of the spinal canal and passed through intervertebral foramina to form paravertebral masses. For thoracic dumbbell-shaped tumors, costotransverse joints and adjacent rib components combined with vertebral laminae, and facet joints on the affected side were resected to expose the total tumor. For lumbar dumbbell-shaped tumors, ipsilateral transversectomy and hemilaminectomy combined with facetectomy were performed to remove the entire tumor. After GTR of dumbbell-shaped tumors in one step, all patients were concurrently treated with unilateral TIF to guarantee spinal stability. Before surgery, the ipsilateral pedicles of adjacent vertebra in one case of the thoracic tumors were involved as indicated by preoperative MRI and CT scans (**Figure 2**). For this patient, unilateral pedicle screw fixation was performed on the unaffected side. For other patients with intact pedicles, unilateral TIF was performed on the lesion side.

The characteristics of patients related to gender, age, involved level, and histopathological type are summarized in **Tables 1** and **2**. For the MIS group, there were eight men and seven women with a median age of 52 years. For the TOS group, there were ten men and eight women with a median age of 55 years. After surgery, they were monitored for at least 5 years. As shown in **Table 3**, the mean length of surgical incision for two groups was 3.47 ± 0.37 vs. 6.49 ± 0.39 cm ($p < 0.05$). The average duration of the operation was 131.67 ± 26.90 vs. 144.17 ± 23.59 min ($p > 0.05$), indicating that there was no significant difference. The mean blood loss was 172.00 ± 48.79 vs. 285.83 ± 99.31 ml ($p < 0.05$). No blood transfusions were required in the two groups. The median length of hospitalization was 6 vs. 10 days (range: 5–8 vs. 7–14 days). During the procedure, pleural disruption occurred in three cases of thoracic dumbbell-shaped tumors. In each of these cases, there was no obvious pneumothorax or hydrothorax on the x-ray immediately after surgery. Closed thoracic drainage was not performed.

Postoperative CT showed that the spinal dumbbell-shaped tumors were completely removed *via* the one-step minimally invasive technique. GTR was achieved in all patients. Histopathological analysis showed that the resected tumors were benign nerve sheath tumors (**Tables 1**, **2**). The patients of two groups were monitored for an average of 65.93 ± 3.88 vs. 65.78 ± 3.56 months. There were no procedure-related complications. All patients returned to normal activities within 4 weeks.

During the follow-up, clinical outcomes were assessed by VAS, ODI, and ASIA. As for pain intensity in the symptomatic region of chief complaint, the preoperative VAS of two groups was 8.47 ± 1.06 vs. 7.89 ± 1.18, indicating that there was no significant difference (**Table 4**). After surgery and 3 months later, VAS score in the MIS group was lower than that in TOS group ($p < 0.05$). At 1-, 2-, and 5-year follow-up, there were no significant differences between MIS and TOS groups in the assessment of VAS score. As for ODI assessment (**Table 5**), the MIS group was higher than the TOS group before surgery, while at 2- and 5-

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TABLE 1 Results of patients performed *via* the minimally invasive technique.

Patient	Gender	Age	Involved level	Histopathological type	ASIA		
					Preop	3-month follow-up	5-year follow-up
1	M	34	L3/4	Ganglioneuromas	E	E	E
2	F	61	T10/11	Neurofibroma	E	E	E
3	M	68	T12/L1	Neurofibroma	E	E	E
4	F	46	T8/9	Ganglioneuromas	E	E	E
5	M	50	L3/4	Neurilemmoma	D	E	E
6	M	47	T7/8	Neurilemmoma	E	E	E
7	M	52	L1/2	Neurofibroma	E	E	E
8	M	18	T5/6	Shwannomas	C	E	E
9	F	54	L5/S1	Neurilemmoma	D	E	E
10	M	58	T12/L1	Neurilemmoma	E	E	E
11	F	57	T11/12	Shwannomas	D	E	E
12	M	62	T7/8	Shwannomas	E	E	E
13	F	49	L2/3	Neurilemmoma	D	E	E
14	F	45	T8/9	Shwannomas	E	E	E
15	F	55	T9/10	Neurofibroma	E	E	E

TABLE 2 Results of patients treated *via* traditional open surgical technique.

Patient	Gender	Age	Involved level	Histopathological type	ASIA		
					Preop	3-month follow-up	5-year follow-up
1	M	65	T7/8	Neurofibroma	E	E	E
2	M	62	T11/12	Neurilemmoma	E	E	E
3	F	55	T10/11	Ganglioneuromas	D	E	E
4	M	66	L3/4	Neurofibroma	E	E	E
5	F	57	T12/L1	Neurilemmoma	D	E	E
6	F	42	T8/9	Shwannomas	E	E	E
7	F	33	L1/2	Neurilemmoma	E	E	E
8	M	40	T9/10	Ganglioneuromas	D	E	E
9	F	27	L4/5	Neurofibroma	E	E	E
10	M	53	T11/12	Neurilemmoma	E	E	E
11	M	67	T9/10	Shwannomas	E	E	E
12	F	41	L1/2	Neurofibroma	E	E	E
13	M	58	T12/L1	Ganglioneuromas	E	E	E
14	M	53	T6/7	Shwannomas	D	E	E
15	F	47	L2/3	Neurilemmoma	E	E	E
16	M	55	T11/12	Neurofibroma	E	E	E
17	F	59	L1/2	Neurilemmoma	D	E	E
18	M	63	T10/11	Neurilemmoma	E	E	E

year follow-up, the MIS group was lower than the TOS group ($p < 0.05$). This indicated that ODI in the MIS group decreased significantly more than the TOS group. As for neurological motor/sensory outcome, ASIA grade improved in all patients. In the MIS group, five patients had improvement of neurological function with ASIA scale to E after 3 months (four from D to E and one from C to E). The remaining 10 patients had normal neurological function (ASIA scale E) preoperatively and postoperatively. In the TOS group, five patients had improvement of neurological function with ASIA scale from D to E after 3 months. The remaining 13 patients had normal neurological function (ASIA scale E) preoperatively and postoperatively. At 5-year follow-up, all patients had normal neurological function (ASIA scale E).

Postoperative x-rays and CT scans demonstrated that the pedicle screws and cages were properly positioned after surgery. During the follow-up period, there were no significant changes in the radiological examinations. No spondylolisthesis and spinal instability were found during the entire follow-up. Fusion of intervertebral segments was achieved in all patients after 2 years, including grade I in 11 segments (73.3%) and grade II in 4 segments (26.7%), based on the Bridwell grading system. No pedicle screw prolapses or rod failures were seen at the final follow-up. There was no recurrence of any spinal tumor 5 years after surgery confirmed by MRI examination (**Figures 5**, **6**).

Discussion

Minimally invasive approach has recently been used to treat spinal disorders to curtail the amount of soft tissue and bone removal. Successful minimally invasive approach of spinal surgery was described in our previous study and other studies regarding treatment of vertebral compression fractures and spinal degenerative pathologies (14–18). Potential advantages include decreased blood loss, lower hospitalization costs, less postoperative pain and narcotic use, shorter hospital stay, and quicker return to daily activities. These studies primarily focused on patients with vertebral compression fractures and degenerative pathologies. Minimally invasive strategies have been rarely reported in spinal dumbbell-shaped tumors. We reported our experience with minimally invasive resections of dumbbell-shaped spinal tumors combined with unilateral TIF.

TOS using open posterior midline approach typically necessitates a lengthy surgical incision. Moreover, it requires extensive dissection of paraspinal muscles from the underlying bony components. Bilateral laminectomies and radical ipsilateral facetectomy are usually performed to expose tumors completely. The open approach is associated with iatrogenic complications such as massive blood loss, sustained postoperative pain, potential wound infection, spinal instability, and deformities. Therefore, MIS for resection of spinal tumors was introduced to reduce approach-related iatrogenic complications. In this study, minimally invasive resection of dumbbell-shaped tumors, whose medial border was located in the extradural region of spinal canal and near the midline of vertebral canal, was performed using a unilateral paraspinal muscle approach with an expandable tubular retractor. Unlike open posterior midline approach, the minimally invasive approach preserves the supraspinous and interspinous ligaments, avoiding extensive stripping of paraspinal muscles from the bony components of the spine while providing adequate access to lamina, facet joints, and transverse processes. Thus, minimally invasive resection of spinal dumbbell-shaped tumors offers some advantages over traditional open resection (19). First, the MIS technique through the paraspinal muscle-splitting approach provides easy access to the dumbbell-shaped tumor after hemilaminectomy and facetectomy, allowing complete resection of tumors without any traction on nerve structures. This is beneficial to prevent postoperative neurological complications. Second, it preserves the ligamentous structures and the attachment of paraspinal muscles to bone, decreasing postoperative pain. Third, it reduces the operative blood loss and shortens the surgical incision and hospital stay. Finally, it facilitates to promote early postoperative rehabilitation of patients. In our study, MIS patients were able to mobilize postoperatively as soon as possible without additional external immobilization devices. However, MIS also presents the disadvantage of prolonged learning curves for surgeons.

TABLE 3 Comparison of variables between two groups.

Variables	MIS	TOS	*p*-value
Operation time (min)	131.67 ± 26.90	144.17 ± 23.59	0.16
Blood loss (ml)	172.00 ± 48.79	285.83 ± 99.31	<0.05
Surgical incision (cm)	3.47 ± 0.37	6.49 ± 0.39	<0.05
Hospitalization (range/median, days)	5–8/6	7–14/10	<0.05
Follow-up period (months)	65.93 ± 3.88	65.78 ± 3.56	0.91

MIS, minimally invasive surgery; TOS, traditional open surgery.

TABLE 4 VAS pain assessment of the two groups.

Group	Preoperative	Postoperative	3 month	12 month	2 year	5 year
MIS	8.47 ± 1.06	2.07 ± 0.88	0.53 ± 0.52	0.27 ± 0.46	0.27 ± 0.46	0.27 ± 0.46
TOS	7.89 ± 1.18	3.83 ± 0.86	1.22 ± 0.81	0.67 ± 0.69	0.50 ± 0.62	0.50 ± 0.62
p-value	0.15	<0.05	<0.05	0.06	0.23	0.23

VAS, visual analog scale; MIS, minimally invasive surgery; TOS, traditional open surgery.

TABLE 5 ODI assessment of the two groups.

Group	Preoperative	2 year	5 year
MIS	79.73 ± 4.27	26.93 ± 6.09	21.20 ± 2.70
TOS	77.00 ± 2.93	35.00 ± 4.77	30.33 ± 3.65
p-value	<0.05	<0.05	<0.05

ODI, Oswestry Disability Index; MIS, minimally invasive surgery; TOS, traditional open surgery.

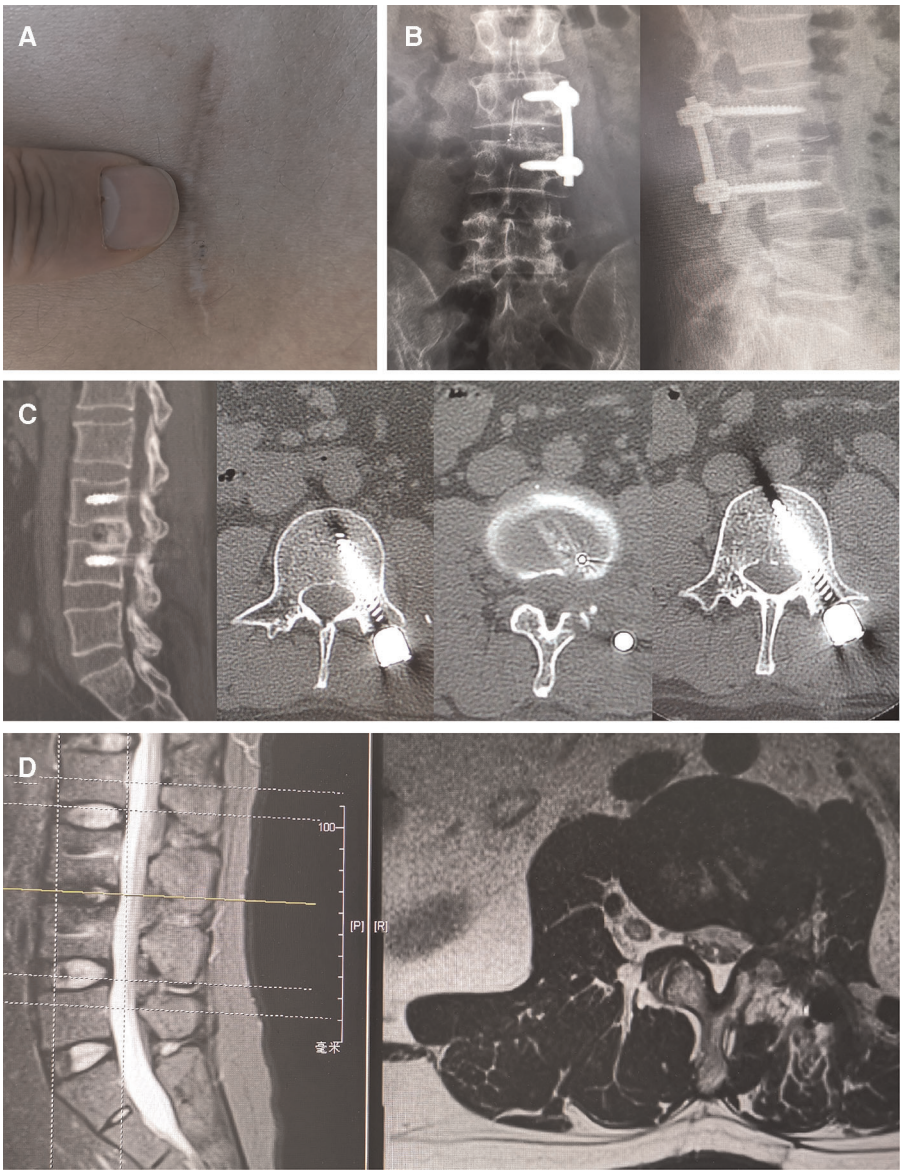

FIGURE 5
X-rays and CT scans showed the fusion of intervertebral segments was achieved, and there was no failure of internal fixation and occurrence of spinal deformity at 5 years after surgery. Grade I fusion was attained in a lumbar dumbbell-shaped tumor patient at 5-year follow-up. There was no recurrence of any spinal tumor 5 years after surgery confirmed by MRI examination. (**A**) The minimally invasive incision was shown 5 years after surgery. (**B**) x-rays; (**C**) CT scans. (**D**) MRI of lumbar dumbbell-shaped tumor patient (case 5).

These spinal dumbbell-shaped tumors pass through the intervertebral foramina to form paravertebral masses. There are two distinct components located in intraspinal and paravertebral compartments. The intraspinal portion of the tumor is located in the intracanal and intraforaminal region of the spinal canal, requiring ipsilateral hemilaminectomy or radical laminectomy combined with facetectomy on the affected side to expose and remove the tumor effectively (20, 21). The paravertebral portion of the tumor is located in extraforaminal region and may extend into the retropleural or retroperitoneal regions. For the paravertebral component extending into the retroperitoneal cavity, laparoscopy-assisted resection has been reported (22). For the paravertebral component extending into the posterior mediastinum, endoscopy-assisted thoracic surgery was performed to resect tumor pieces safely (23). Even for large retropleural components or for tumors in hard-to-reach locations, thoracoscopic surgery was effective for removal (24). In previous studies of thoracic dumbbell-shaped tumor treatment, the combination of thoracoscopic and posterior spinal surgery has been proven to be a successful alternative surgical procedure (25,

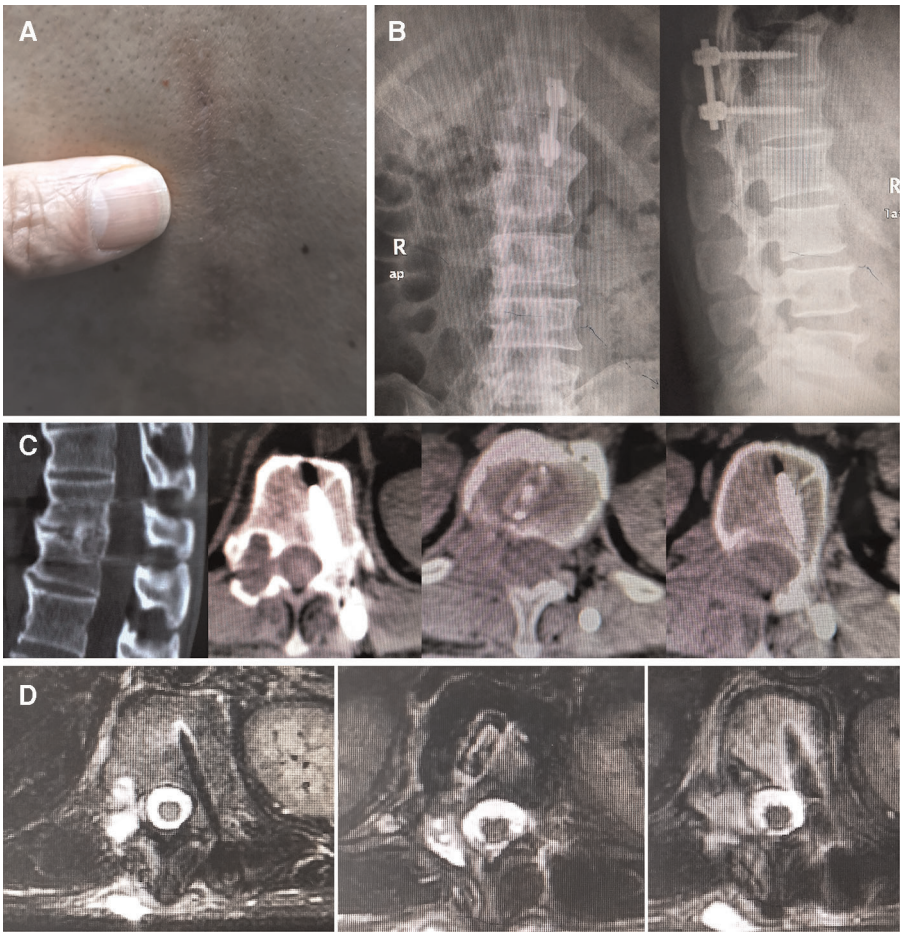

FIGURE 6
X-rays and CT scans showed the fusion of intervertebral segments was achieved, and there was no failure of internal fixation and occurrence of spinal deformity at 5 years after surgery. Grade I fusion was attained in a thoracic dumbbell-shaped tumor patient without fatigue of instrumentation at 5-year follow-up. There was no recurrence of any spinal tumor 5 years after surgery confirmed by MRI examination. (**A**) The minimally invasive incision was shown 5 years after surgery. (**B**) x-rays; (**C**) CT scans. (**D**) MRI of thoracic dumbbell-shaped tumor patient (case 15).

26). Nevertheless, there are various complications of thoracoscopic surgery, including pulmonary complication, intercostal neuralgias, shoulder girdle dysfunction, and chronic postoperative pain syndromes (27, 28). If spinal dumbbell-shaped tumors can be resected directly in one step, complications can be reduced. Payer et al. reported the excision of a dumbbell-shaped tumor using a single posterior midline approach with laminectomy and costotransversectomy (29). Rzyman et al. reported one-step removal of thoracic dumbbell-shaped tumors performed by the thoracic team alone through a posterolateral thoracotomy and extended foraminectomy (30). In our study, whether for thoracic or lumbar dumbbell-shaped tumors, the paravertebral component can be directly exposed and resected completely after removal of transverse processes or costotransverse joints and adjacent rib components in one step through minimally invasive approach. If the tumor border is clear, surgeons can use their fingers to separate and completely pull out the paravertebral part of the tumor; otherwise, piecemeal excision of the tumor could be performed. This technique avoids another transthoracic or retroperitoneal surgery to remove the paravertebral mass and reduces the rate of procedure-related complications.

Laminectomy and facetectomy usually result in spinal instability and deformity, which are of particular concern after multilevel laminectomy and facetectomy (31). Papagelopoulos et al. reported that spinal instability and deformity after multilevel laminectomy for resection of spinal tumors were not uncommon in children and young adults, and necessitated the fusion of intervertebral segments to correct postoperative deformity and stabilize the spine (32). In this study, unilateral hemilaminectomy and total facetectomy were performed to expose and resect dumbbell-shaped tumors. The biomechanical stability of the spine was largely destroyed because of the resection of the hemilamina and facet joint. Katsumi et al. reported that the occurrence of postoperative spinal deformity or instability was about 20% resulting from

laminectomies for resection of spinal tumor (33). In another retrospective study by Wiedemayer et al., the occurrence of postoperative spinal deformity or instability was about 30% even when the laminar roof was reconstructed using titanium miniplates after laminectomies for resection of spinal tumor (34). In this study, with the aim of minimizing the occurrence of postoperative spinal instability and deformity, unilateral TIF was performed after resection of spinal dumbbell-shaped tumors. At the final follow-up, fusion of intervertebral segments was achieved in all patients, and there was no failure of internal fixation and occurrence of spinal deformity. This suggests that unilateral TIF provides sufficient mechanical support for spinal stability and prevents spinal deformity associated with postoperative axial back pain. Through the minimally invasive incision performed for resection, the pedicle screws and cages could be implanted for unilateral TIF without additional intraoperative disruption. Sometimes, even though the pedicles of superior and inferior vertebrae adjacent to tumor were damaged, unilateral pedicle screw fixation was performed on the contralateral side and the cage was inserted from the lesion side after the complete removal of tumor through a mini posterior midline incision and bilateral paraspinal muscle-splitting approaches.

Like all other surgical techniques, pedicle screw fixation is not without risk, as it can violate the spinal canal or neuroforamen to cause nerve injuries. In our study, the pedicles were located and probed in all four quadrants to ensure that a solid bone tube was present and no violation into the spinal canal or inferiorly into the neuroforamen occurred. During the follow-up, none of the patients were found to have any postoperative neurological complications. The postoperative x-ray and CT images showed that the pedicle screws and cages were properly positioned in all patients. The fusion of intervertebral segments was secure in all patients and no hardware failure was seen in any patient at the final follow-up. These findings suggest that this technique avoids procedure-related neurological deficits and guarantees safety of operation.

The efficacy of total resection and postoperative recovery is also of concern in the treatment of spinal dumbbell-shaped tumors. In this study, the dumbbell-shaped tumors in all patients were completely removed, and all patients showed improvement of neurological function after surgery in both MIS and TOS groups. For the minimally invasive technique, the operation-related variables (length of surgical incision, blood loss, hospital stay) and postoperative outcome in terms of pain improvement and procedure-related complications were superior to traditional open or other techniques (35).

Conclusions

Minimally invasive resection through the paraspinal muscle approach combined with unilateral TIF in one step is a safe and effective surgical technique. Ipsilateral hemilaminectomy and facetectomy are sufficient to remove the intraspinal portion, and the paravertebral portion extending into the retropleural or retroperitoneal region can be concurrently removed after excising transverse processes or costotransverse joints and adjacent rib components. Following these procedures, unilateral TIF is performed to prevent postoperative spinal instability and deformity. If the pedicles adjacent to the tumor are not involved and intact, unilateral TIF is advocated on the lesion side. If the pedicles are involved, cages are inserted from the lesion side and unilateral pedicle screw fixation was performed on the contralateral side. Compared with traditional open technique, minimally invasive surgery offers a reduced length of surgical incision, blood loss, hospital stay, and postoperative pain.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving human participants were reviewed and approved by Ethics Committee of Zhongshan Hospital. The ethics committee waived the requirement of written informed consent for participation.

Author contributions

All authors contributed to the conception and design of study. Analysis and acquisition of data were performed by JP and YG. The manuscript was written by JP and revised by YG and FZ. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

1. Jinnai T, Hoshimaru M, Koyama T. Clinical characteristics of spinal nerve sheath tumors: analysis of 149 cases. *Neurosurgery*. (2005) 56(3):510–5. doi: 10.1227/01.NEU.0000153752.59565.BB

2. Celli P, Trillo G, Ferrante L. Extrathecal intraradicular nerve sheath tumor. *J Neurosurg Spine*. (2005) 3(1):1–11. doi: 10.3171/spi.2005.3.1.0001

3. Xu HP, Rozanski C, Taub PJ. The value of plastic surgery spinal closures a review of 782 spine cases. *Ann Plast Surg*. (2019) 83(2):201–5. doi: 10.1097/SAP.0000000000001831

4. Fessler RG, Khoo LT. Minimally invasive cervical microendoscopic foraminotomy: an initial clinical experience. *Neurosurgery*. (2002) 51(5 Suppl):S37–S45. doi: 10.1097/00006123-200211002-00006

5. Khoo LT, Fessler RG. Microendoscopic decompressive laminotomy for the treatment of lumbar stenosis. *Neurosurgery*. (2002) 51(5 Suppl):S146–54. doi: 10.1097/00006123-200211002-00020

6. Wang MY, Cummock MD, Yu Y, Trivedi RA. An analysis of the differences in the acute hospitalization charges following minimally invasive versus open posterior lumbar interbody fusion. *J Neurosurg Spine*. (2010) 12(6):694–9. doi: 10.3171/2009.12.SPINE09621

7. Bresnahan L, Ogden AT, Natarajan RN, Fessler RG. A biomechanical evaluation of graded posterior element removal for treatment of lumbar stenosis comparison of a minimally invasive approach with two standard laminectomy techniques. *Spine*. (2009) 34(1):17–23. doi: 10.1097/BRS.0b013e318191438b

8. Ogden AT, Bresnahan L, Smith JS, Natarajan R, Fessler RG. Biomechanical comparison of traditional and minimally invasive intradural tumor exposures using finite element analysis. *Clin Biomech*. (2009) 24(2):143–7. doi: 10.1016/j.clinbiomech.2008.11.005

9. Wong AP, Lall RR, Dahdaleh NS, Lawton CD, Smith ZA, Wong RH, et al. Comparison of open and minimally invasive surgery for intradural-extramedullary spine tumors. *Neurosurg Focus*. (2015) 39(2):E11. doi: 10.3171/2015.5.FOCUS15129.

10. Li CB, Ye Y, Gu YT, Dong J. Minimally invasive resection of extradural dumbbell tumors of thoracic spine: surgical techniques and literature review. *Eur Spine J*. (2016) 25(12):4108–15. doi: 10.1007/s00586-016-4677-z

11. Nzokou A, Weil AG, Shedid D. Minimally invasive removal of thoracic and lumbar spinal tumors using a nonexpandable tubular retractor. *J Neurosurg Spine*. (2013) 19(6):708–15. doi: 10.3171/2013.9.SPINE121061

12. Yang YH, Ren MY, Yuan ZQ, Li K, Zhang ZP, Zhang J, et al. Thoracolumbar paravertebral giant ganglioneuroma and scoliosis: a case report and literature review. *World J Surg Oncol*. (2016) 14:65. doi: 10.1186/s12957-016-0823-7

13. Bridwell KH, Lenke LG, McEnery KW, Baldus C, Blanke K. Anterior fresh frozen structural allografts in the thoracic and lumbar spine. Do they work if combined with posterior fusion and instrumentation in adult patients with kyphosis or anterior column defects? *Spine*. (1995) 20(12):1410–8. doi: 10.1097/00007632-199506020-00014

14. Oh T, Scheer JK, Fakurnejad S, Dandaleh NS, Smith ZA. Minimally invasive spinal surgery for the treatment of traumatic thoracolumbar burst fractures. *J Clin Neurosci*. (2015) 22(1):42–7. doi: 10.1016/j.jocn.2014.05.030

15. Mobbs RJ, Sivabalan P, Li J. Minimally invasive surgery compared to open spinal fusion for the treatment of degenerative lumbar spine pathologies. *J Clin Neurosci*. (2012) 19(6):829–35. doi: 10.1016/j.jocn.2011.10.004

16. Gu YT, Zhu DH, Liu HF, Zhang F, McGuire R. Minimally invasive pedicle screw fixation combined with percutaneous vertebroplasty for preventing secondary fracture after vertebroplasty. *J Orthop Surg Res*. (2015) 10:31. doi: 10.1186/s13018-015-0172-1

17. Gu YT, Zhang F, Jiang XX, Jia LS, McGuire R. Minimally invasive pedicle screw fixation combined with percutaneous vertebroplasty in the surgical treatment of thoracolumbar osteoporosis fracture. *J Neurosurg Spine*. (2013) 18(6):634–40. doi: 10.3171/2013.3.SPINE12827

18. Li CB, Pan JF, Gu YT, Dong J. Minimally invasive pedicle screw fixation combined with percutaneous vertebroplasty for the treatment of thoracolumbar burst fracture. *Int J Surg*. (2016) 36:255–60. doi: 10.1016/j.ijsu.2016.11.003

19. Kerimbayev TT, Tuigynov ZM, Aleinikov VG, Urunbayev YA, Kenzhegulov YN, Baiskhanova DM, et al. Minimally invasive posterolateral approach for surgical resection of dumbbell tumors of the lumbar spine. *Front Surg*. (2022) 9:792922. doi: 10.3389/fsurg.2022.792922

20. Millward CP, Bhagawati D, Chan HW, Bestwick J, Brecknell JE. Retrospective observational comparative study of hemilaminectomy versus laminectomy for intraspinal tumour resection; Shorter stays, lower analgesic usage and less kyphotic deformity. *Brit J Neurosurg*. (2015) 29(3):390–5. doi: 10.3109/02688697.2014.1003026

21. Li HB, Weng YP, Zhou D, Nong LM, Xu NW. Experience of operative treatment in 27 patients with intraspinal neurilemmoma. *Oncol Lett*. (2017) 14(4):4817–21. doi: 10.3892/ol.2017.6799

22. Shi W, Su X, Li WG, Xu XD, Huang JF, Chen J. Laparoscopic-assisted resection for retroperitoneal dumbbell-shaped lumbar spinal schwannomas: operative technique and surgical results. *World Neurosurg*. (2016) 91:129–32. doi: 10.1016/j.wneu.2016.03.106

23. Konno S, Yabuki S, Kinoshita T, Kikuchi S. Combined laminectomy and thoracoscopic resection of dumbbell-type thoracic cord tumor. *Spine*. (2001) 26(6):E130–4. doi: 10.1097/00007632-200103150-00005

24. Barrenechea IJ, Fukumoto R, Lesser JB, Ewing DR, Connery CP, Perin NI. Endoscopic resection of thoracic paravertebral and dumbbell tumors. *Neurosurgery*. (2006) 59(6):1195–201, discussion 201–2. doi: 10.1227/01.NEU.0000245617.39850.C9

25. Ohya J, Miyoshi K, Kitagawa T, Sato Y, Maehara T, Mikami Y. Combined video-assisted thoracic surgery and posterior spinal surgery for the treatment of dumbbell tumor of the first thoracic nerve root. *Asian Spine J*. (2015) 9(4):595–9. doi: 10.4184/asj.2015.9.4.595

26. Tanaka T, Kato N, Aoki K, Nakamura A, Watanabe M, Tochigi S, et al. Combined unilateral hemilaminectomy and thoracoscopic resection of the dumbbell-shaped thoracic neurinoma: a case report. *Case Rep Neurol Med*. (2012) 2012:517563. doi: 10.1155/2012/517563

27. Ponce FA, Killory BD, Wait SD, Theodore N, Dickman CA. Endoscopic resection of intrathoracic tumors: experience with and long-term results for 26 patients clinical article. *J Neurosurg Spine*. (2011) 14(3):377–81. doi: 10.3171/2010.11.SPINE09718

28. Landreneau RJ, Hazelrigg SR, Mack MJ, Dowling RD, Burke D, Gavlick J, et al. Postoperative pain-related morbidity: video-assisted thoracic surgery versus thoracotomy. *Ann Thorac Surg*. (1993) 56(6):1285–9. doi: 10.1016/0003-4975(93)90667-7

29. Payer M, Radovanovic I, Jost G. Resection of thoracic dumbbell neurinomas: single postero-lateral approach or combined posterior and transthoracic approach? *J Clin Neurosci*. (2006) 13(6):690–3. doi: 10.1016/j.jocn.2005.09.010

30. Rzyman W, Skokowski J, Wilimski R, Kurowski K, Stempniewicz M. One step removal of dumb-bell tumors by postero-lateral thoracotomy and extended foraminectomy. *Eur J Cardiothorac Surg*. (2004) 25(4):509–14. doi: 10.1016/j.ejcts.2003.12.022

31. Guigui P, Benoist M, Deburge A. Spinal deformity and instability after multilevel cervical laminectomy for spondylotic myelopathy. *Spine*. (1998) 23(4):440–7. doi: 10.1097/00007632-199802150-00006

32. Papagelopoulos PJ, Peterson HA, Ebersold MJ, Emmanuel PR, Choudhury SN, Quast LM. Spinal column deformity and instability after lumbar or thoracolumbar laminectomy for intraspinal tumors in children and young adults. *Spine*. (1997) 22(4):442–51. doi: 10.1097/00007632-199702150-00019

33. Katsumi Y, Honma T, Nakamura T. Analysis of cervical instability resulting from laminectomies for removal of spinal cord tumor. *Spine*. (1989) 14(11):1171–6. doi: 10.1097/00007632-198911000-00007

34. Wiedemayer H, Sandalcioglu IE, Aalders M, Wiedemayer H, Floerke M, Stolke D. Reconstruction of the laminar roof with miniplates for a posterior approach in intraspinal surgery: technical considerations and critical evaluation of follow-up results. *Spine*. (2004) 29(16):E333–42. doi: 10.1097/01.BRS.0000134592.07941.5E

35. Li YW, Wang B, Li L, Lu GH. Posterior surgery versus combined laminectomy and thoracoscopic surgery for treatment of dumbbell-type thoracic cord tumor: a long-term follow-up. *Clin Neurol Neurosurg*. (2018) 166:31–5. doi: 10.1016/j.clineuro.2018.01.019

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Stand-alone anterior cervical decompression and fusion surgery: A cohort study evaluating a shaped cage without plates or screws

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Background: The anterior approach to the cervical spine is the most commonly used surgery with effective decompression and less surgical trauma. Anterior plate construct (APC) is considered a standard technique. However, it appears to cause implant failure and postoperative dysphagia. Due to these reasons, locking stand-alone cages (LSCs) without the addition of an anterior plate have been developed and gained popularity in the past decade. In theory, an LSC could provide immediate load-bearing support to the anterior column of the cervical spine and may enhance the rate of arthrodesis. However, screw skiving and backing off are known complications of LSC. Given the characteristic shape of cervical discs, we wondered whether there may be a role for a shape-conforming cage without screws and plates to achieve desired outcomes, i.e., a true stand-alone cage (TSC). A single surgeon cohort using the cage in a heterogenic set of indications was evaluated.

Methods: A total of 45 patients with degenerative cervical conditions who underwent surgery using TSC using CoRoent Small Contoured peek cage (Nuvasive, San Diego, CA) and Orthoblend™ (Medtronics, Memphis, TN) were retrospectively reviewed. Comparisons between preoperative and postoperative Numeric Rating Scale (NRS), the modified AAOS-Modems disability outcome, Neck Disability Index (NDI) scores, and Short Form 36 were evaluated. Operative time, the occurrence rate of fusion, lordosis change of cervical spine, and occurrence rate of complications were evaluated.

Results: There were one-level ($n = 15$), two-level ($n = 24$), and three-level ($n = 6$) cases making a total of 81 cages implanted and studied. The mean operative time was 132.7 min. The group demonstrated significant improvements in NRS, AAOS-Modems disability outcome, and NDI scores after surgery (mean follow-up 12 months). The cervical lordosis at pre- and last follow-up period was $8.7 \pm 2.2°$ and $8.3 \pm 3.2°$, respectively. The complication rate was 21.2%.

Conclusions: TSC yielded satisfactory long-term clinical and radiological outcomes; this preliminary report can form the basis of a cost–benefit analysis study either prospectively or by way of meta-modeling comparing APC, LSC to TSC.

KEYWORDS

cervical spondylotic conditions, anterior decompression, fusion, stand-alone cage, complication

Introduction

Anterior cervical discectomy and fusion (ACDF) has been considered the standard surgical intervention for the treatment of cervical spondylotic conditions (e.g., a degenerative cervical disease with myelopathy or radiculopathy) (1, 2). The goal of this surgery is intended to obtain effective neural (e.g., spinal cord and nerve root) decompression, maintain the affected segment stabilization, and restore lordosis of the cervical spine (3, 4).

Anterior plate construct (APC) is a commonly used technique for ACDF (5). Traditionally, the anterior plate is used for maintaining the stabilization of the cervical spine, improving cervical lordotic alignment, increasing fusion rate, and preventing cage dislocation (6). However, the use of an anterior plate may lead to some potential adverse events, such as sore throat, dysphagia, implant failure, and adjacent segment degeneration (ASD). Due to these reasons, locking stand-alone cages (LSCs) without the anterior plate has been developed and gained popularity in the past decade (1). In theory, an LSC could provide immediate load-bearing support to the anterior column of the cervical spine and may enhance the rate of arthrodesis. Previous studies reported that LSC provided comparable stability and reduced the damage to soft tissues and plate-related complications with a satisfactory clinical outcome (7–12). Nevertheless, previously published studies showed that there were no advantages of LSC in clinical and/or radiologic outcomes and/or complications compared with APC (13, 14). Some complications following LSC have been reported, including screw skiving and backing off. Therefore, a consensus has not yet been arrived at on the efficacy of LSC in the reduction of neck pain and overall complications in cervical spondylotic conditions. Given the characteristic shape of cervical discs, we wondered whether there may be a role for a shape-conforming cage without screws and plates to achieve desired outcomes, i.e., a true stand-alone cage (TSC).

To further clarify arguments in the current literature, a single surgeon cohort using the cage (e.g., TSC) through a minimally invasive approach for treating the patients with a heterogenic set of indications was evaluated.

Participants and methods

Ethical approval was obtained from the Human Research Ethics Committee of the University of New South Wales (NRR-HC210096) for the retrospective analysis of outcomes (e.g., demographic data, clinical outcome, and radiological outcome) of patients who have undergone stand-alone anterior cervical decompression and fusion surgery (TSC without the addition of an anterior plate) at Spine Service, St George Hospital Campus (UNSW Sydney, Australia).

Design and patients

Inclusion criteria were the following: (1) age more than 18 years; (2) signs and symptoms of cervical spondylotic conditions (e.g., cervical radiculopathy or cervical spondylotic myelopathy); (3) cervical spondylotic conditions confirmed using magnetic resonance imaging; (4) patients signed the informed consent; and (5) at least of 3 months follow-up after surgery. Exclusion criteria were the following: (1) developmental cervical spinal stenosis; (2) ossification of the posterior longitudinal ligament; (3) systemic or local infection; (4) trauma, fracture, tumor, and invasive malignancy; and (5) surgical history of the cervical spine.

Neurological assessment and clinical outcomes

Primary symptoms (e.g., symptoms for myelopathy or radiculopathy) including any hand–neck pain, clumsiness, radicular pain to the upper limb(s), leg stiffness, and gait disturbance were recorded. The Neck Disability Index (NDI) and Numeric Rating Scale (NRS) were used to assess disability and neck and radicular pain, respectively. The neck pain relief was rated with 6 points [score 1 = complete relief (100%); score 2 = small amount of symptoms persists (80%–99%); score 3 = most of symptoms are gone (60%–0%); score 4 = moderate relief (30%–60%); score 5 = minor relief (up to 30%); score 6 = no relief or symptoms worse]. Eighteen items were included in the modified AAOS-Modems disability outcome tool spine-service version for the physical functioning scale (PFS). Each item of this tool was manually rated with 5 points for one of three possible responses (score 0 = not limited at all, score 3 = little limitation, and score 5 = limited quite a lot). We obtained scores for the eight Short Form 36 (SF-36) subscales [physical functioning (PF), energy fatigue (EF), emotional wellbeing (EW), social functioning (SF), bodily pain (BP), general health (GH)]. All the data were collected preoperatively, at 1-month, 3-month, 6-month, 12-month, and last follow-up after surgery. The senior spinal surgeon with 30 years of experience (ADD) performed the neurological assessment and surgery.

Surgical technique

Patients were placed in the supine position. The surgical procedure was exposed through a standard anterior approach from the left side. Small access corridors were used to minimize the

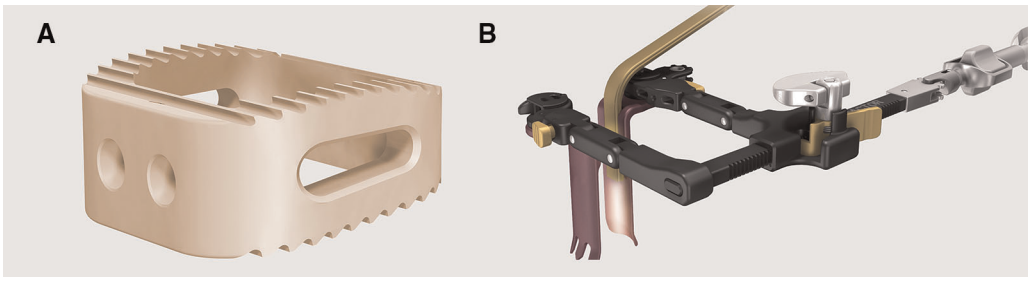

FIGURE 1
(A) CoRoent small contoured peek cage (Nuvasive, San Diego, CA). (B) Anterior retractors systems (Maxcess C retractor, Nuvasive San Diego CA).

damage to soft tissue. In order to obtain better visualization and illumination, the better anterior retractor systems (Maxcess C retractor, Nuvasive, San Diego, CA, Figure 1) were combined with the use of the loupes. This retractor system optimizes direct illumination using a cold light source directly attached to the retraction blade. Furthermore, the retractor is stabilized to the operating table diminishing needless retractor movement on soft tissue during the operation. For multilevel procedures, the retractors are moved one level at a time with segmental Casper pin distraction. Anterior cervical discectomy was performed. After dural and root decompression, patients underwent TSC using CoRoent Small Contoured peek cage (Nuvasive, San Diego, CA, Figure 1) and Orthoblend™ (Medtronics, Memphis, TN). The cages were filled with demineralized bone matrix for augmenting fusion.

The technique allows minimal dissection and smaller incisions, and allows for maximal spinal canal decompression and disc clearance through a minimally invasive technique.

Radiological evaluation

The preoperative and postoperative lordosis of the cervical spine, postoperative fusion rate, and postoperative subsidence were measured and evaluated *via* radiological images. The lordosis of the cervical spine was measured by the Cobb angle between the inferior endplate of C2 to the inferior endplate of C7 (Figure 2) (15). The definition of fusion was listed as (1) the range of motion of surgical level <2° in postoperative radiographs, (2) the formation of bridging trabecular bone between the involved vertebral bodies; and (3) the absence of a radiolucent gap through the fusion level. The incidence of subsidence was referred to as more than 3 mm reduction of the disc height in the involved level in postoperative images (16).

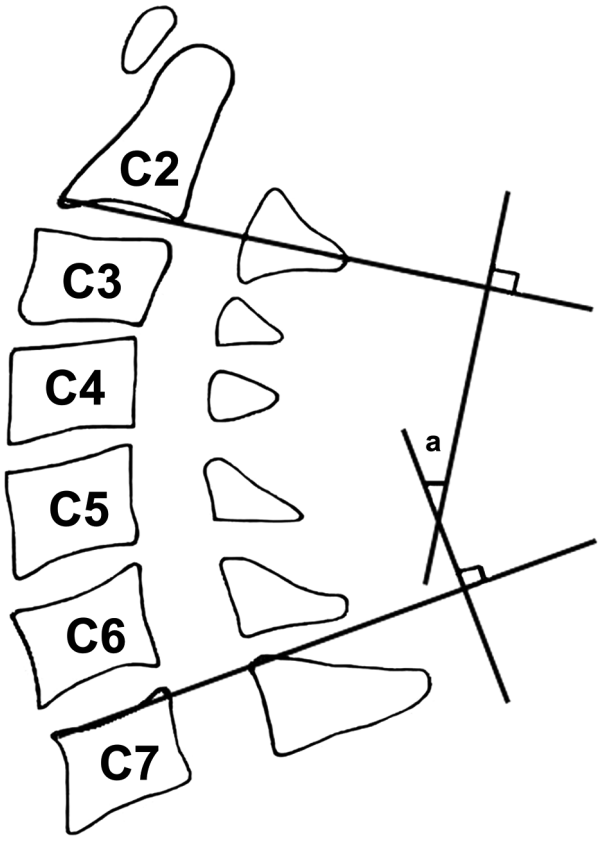

FIGURE 2
Cobb angle for measuring cervical lordosis. Cobb angle is measured on lateral x-ray of the lumbar spine: the angle (a) is formed by the inferior endplate of the C2 to the inferior endplate of the C7.

Surgical complications

Procedure-related and postoperative complications at each follow-up time point were evaluated and collected by a clinical fellow (AS). Procedure-related complications include injury to recurrent laryngeal nerve, dural tear, nerve root damage, damage to the spinal cord, major blood vessel injury, infection, and damage to the trachea or esophagus. Postoperative complications include inadequate symptom relief after the surgery, pseudarthrosis, dysphasia, potential speech disturbance, hematoma, and ASD.

Statistical analysis

The continuous variables were expressed as mean ± standard deviation (SD). Paired *t*-test was used to compare the clinical outcomes of NRS and NDI between preoperative and final follow-up. Due to the non-normal distribution of these data, the nonparametric Mann–Whitney *U* test was used to compare the NRS, NDI, PFS, PF, EF, EW, SF, BP, and GH between the preoperative and final follow-up groups. Categorical variable data were analyzed by Fisher's exact test. SPSS v24.0 (SPSS Inc., Chicago, IL, United States) was used for the statistical analysis. $P < 0.05$ was considered to be statistically significant.

Results

Patients

This study included 45 patients (20 females and 25 males), aged 40–75 years (the mean age at surgery was 52.4 years), operated in our department by a senior surgeon (ADD) between November 2012 and January 2021, and having complete pre- and postoperative clinical and radiological data. The mean time to follow-up was 12 months (range 6–24 months). Fifteen cases with one-level, 24 cases with two-level, and six cases with three-level made a total of 81 cages implanted and studied (Table 1 and Figure 3).

Clinical outcomes

All patients reported at least partial improvement in pain scale and functional status during the last follow-up

TABLE 1 Demographics and clinical data.

Characteristic	Value
No. of patients	45
Mean of age (years)	52.4 ± 10.6
Female:male	20 (44.4%):25 (55.6%)
Indications	
No. of neck pain	45 (100%)
No. of radiculopathy	38 (84.4%)
No. of myelopathy	40 (88.9%)
Levels	
Single level	15 (33.3%)
Two levels	24 (53.4%)
Three levels	6 (13.3%)
Operative time (minutes)	132.7 ± 32.2
Preoperative lordosis (°)	8.7 ± 2.2

Values are presented as number, number (%), or mean ± standard deviation.

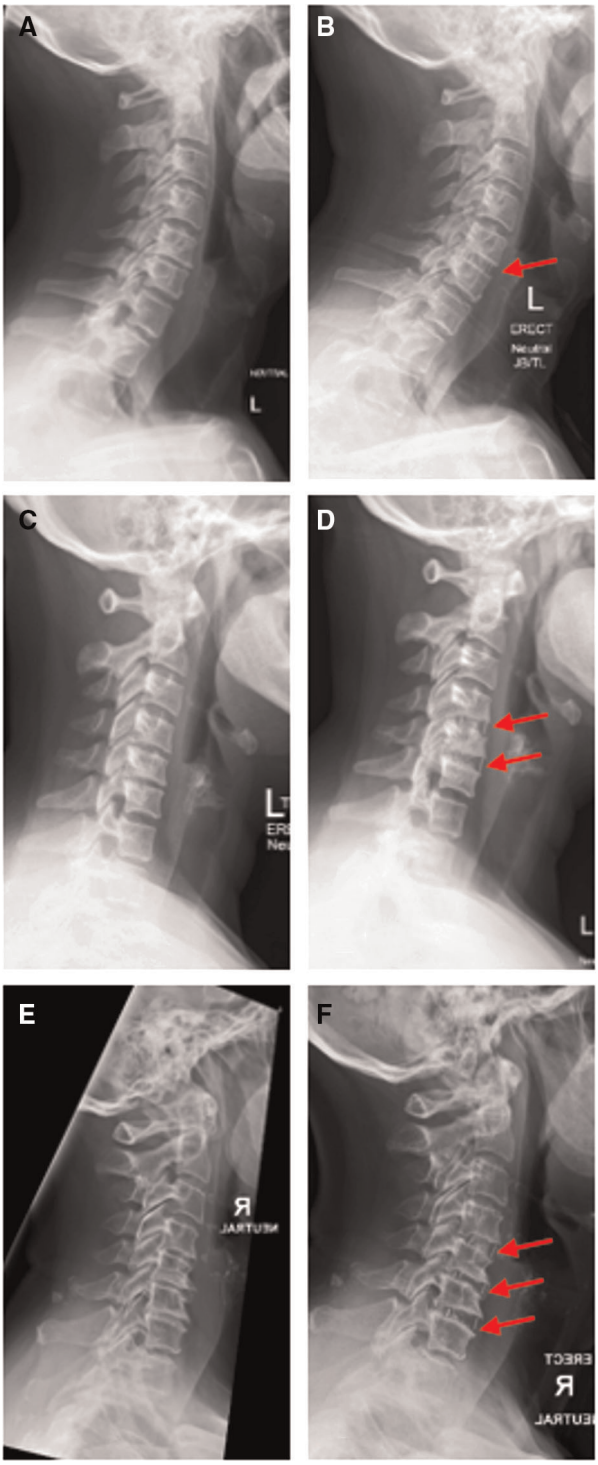

FIGURE 3
(A,B) Standing lateral x-ray of the true stand-alone cage for cervical degenerative disc disease in one-level (C5/6) preoperatively and at 2-year follow-up. (C,D) Standing lateral x-ray of the true stand-alone cage for cervical degenerative disc disease in two levels (C5/6 and C6/7) preoperatively and at 1-year follow-up. (E,F) Standing lateral x-ray of the true stand-alone cage for cervical degenerative disc disease of three levels (C4/5, C5/6, and C6/7) preoperatively and at 1-year follow-up.

TABLE 2 Clinical outcomes of patients preoperatively and at last postoperative follow-up.

	Pre-op	Post-op	*P* value
NRS	6.3 ± 0.4	2.1 ± 0.1	0.000**
NDI	25.2 ± 8.2	17.3 ± 9.9	0.002*
Modified AAOS-Modems disability outcome tool spine-service version			
Vigorous activities	1.8 ± 1.5	1.8 ± 1.3	1.000
Moderate activities	1.9 ± 1.3	2.4 ± 1.5	0.387
Lifting or carrying groceries	2.2 ± 1.3	2.2 ± 1.3	1.000
Climbing several flights of stairs	3.0 ± 1.6	2.7 ± 1.8	0.613
Climbing one flight of stairs	3.6 ± 1.5	3.2 ± 1.9	0.190
Bending, kneeling, stooping	2.5 ± 1.5	2.7 ± 1.8	0.776
Walking more than 1.5 km	2.7 ± 1.8	3.3 ± 1.8	0.165
Walking several blocks	2.8 ± 1.7	3.3 ± 1.8	0.387
Walking one block	3.5 ± 1.5	3.9 ± 1.6	0.337
Sitting	3.2 ± 1.0	3.6 ± 1.3	0.273
Standing erect	2.8 ± 1.3	3.3 ± 1.4	0.273
Lying on back	2.8 ± 1.3	3.2 ± 1.0	0.436
Lying on stomach	3.0 ± 1.4	2.8 ± 1.5	0.721
Lying on sides	2.7 ± 1.4	2.8 ± 1.3	0.776
Grooming or bathing self	3.6 ± 1.5	3.3 ± 1.6	0.584
Sexual activities	2.2 ± 1.7	2.7 ± 1.8	0.273
Initiating gait	3.5 ± 1.7	3.8 ± 1.5	0.502
Crossing streetlights	3.8 ± 1.7	3.8 ± 1.7	1.000
SF-36			
Physical functioning	40.8 ± 20.8	44.1 ± 35.2	0.635
Energy fatigue	37.5 ± 22.8	37.5 ± 20.6	0.953
Emotional well being	51.7 ± 29.9	55.6 ± 27.5	0.944
Social functioning	52.5 ± 27.5	56.3 ± 34	0.610
Pain	33.0 ± 17.8	40.8 ± 27.4	0.326
General health	50.8 ± 22.7	40.5 ± 18.6	0.108

All data are presented as mean ± standard deviation (SD).
Pre-op, preoperative; Post-op, postoperative; NDI, Neck Disability Index; NRS, Numeric Rating Scale; SF-36, Short Form-36.
Significant difference: *P < 0.01, **P < 0.001 (paired t-test).

evaluation. NRS score improved from 6.3 (±0.4) to 2.1 (±0.1) and NDI score improved from 25.2 (±8.2) to 17.3 (±9.9). All scores (e.g., NRS and NDI) exhibited statistically significant improvement at the last follow-up postoperatively ($P < 0.05$). There were no statistically significant differences between the preoperative and last follow-up postoperative data in the modified AAOS-Modems disability outcome, PF, EF, EW, SF, BP, and GH (all $P > 0.05$) using the nonparametric Mann–Whitney *U* test (Table 2).

Radiological outcomes

The fusion rate of patients undergoing ACDF following TSC was documented in 88.9% (40/45) of patients, and 93.3% (14/15) of patients achieved postoperative fusion in the one-level disease group, 87.5% (21/24) of patients with the two-level group, and 83.3% (5/6) of patients with the three-level group. There was no statistically significant difference in NRS and NDI scores between the fusion and no-fusion groups (Table 3).

TABLE 3 Clinical and radiological outcomes.

	Number (%)	*P* value
Fusion rate	40 (88.9%)	1.000
Single level	14 (93.3%)	
Two levels	21 (87.5%)	
Three levels	5 (83.3%)	
Fusion NRS	2.1 ± 1.1	1.000
No-fusion NRS	2.2 ± 0.4	
Fusion NDI	17.0 ± 9.7	0.490
No-fusion NDI	21.2 ± 8.3	
Subsidence	40 (88.9%)	1.000
Single level	14 (93.3%)	
Two levels	21 (87.5%)	
Three levels	5 (83.3%)	
Subsidence NRS	2.1 ± 1.1	0.381
No-subsidence NRS	1.4 ± 1.5	
Subsidence NDI	17.4 ± 9.5	0.942
No-subsidence NDI	17.6 ± 10.5	

NRS, Numeric Rating Scale; NDI, Neck Disability Index.

Cage subsidence was found in five patients (11.1%) at the last follow-up. No significant difference was found between single- and multilevel procedures in the incidence of cage subsidence. There was no statistically significant difference in NRS and NDI scores between the subsidence and no-subsidence groups. The cervical lordosis at the preoperative and last follow-up period was 8.7 ± 2.2° and 8.3 ± 3.2°, respectively (Table 3).

Surgical complications

Seven patients had complications following TSC surgery, including dysphagia in one patient, nausea in two patients, sacrum pressure injury in one patient, wound issue in one patient, and chest pain in one patient. None of them underwent revision surgery.

Discussion

We have demonstrated that in a cohort of patients undergoing TSC-based single- to multilevel fusion a strong basis for feasibility, safety, and preliminary efficacy for a device being currently used with APC fusion. Whilst no

superiority claims are made over APC, we believe that our study forms a good basis for delivering Value-based care with potential for lower complications and potential improved cost-benefit.

APC as the standard technique in ACDF is effective in maintaining cervical stabilization, improving cervical lordotic alignment, preventing cage dislocation, and increasing fusion rates. Previous studies showed the efficacy and safety of using ACDF with cage and plate for signal level or multilevel patients with cervical spondylotic conditions (15, 17). However, increased complication rates associated with plate fixation have been reported in patients with multilevel ACDF (15, 17). In order to overcome these complications, stand-alone cages were developed and used. However, the understanding of these potential disadvantages (e.g., changes in cervical alignment, cage migration, low fusion rates, and the occurrence of subsidence) of using stand-alone cages for treating cervical spondylotic conditions remains incomplete (18). Compared to ACDF (e.g., APC), TSC could theoretically reduce the surgical trauma to soft tissues and reduce blood loss during the surgery, in single- and multilevel procedures. Our study achieved a good clinical efficacy (e.g., significant improvement in NRS and NDI scores) with TSC for single- and multilevel cervical spondylotic conditions.

Plate dislodgement, tracheoesophageal lesions, and dysphagia are recognized as the most occurred complications after ACDF using an additional anterior plate. Previous studies reported that the incidence of transient and chronic dysphagia following ACDF surgery ranges from 2% to 71% and from 3% to 21%, respectively (19). Transient dysphagia occurred in one patient that lasted 4–7 days in the present study (2.2%). None of the patients exhibited permanent dysphagia. A possible explanation for the occurrence of dysphagia following an anterior plate with APC is that the design and fixation of the anterior plate may lead to esophageal injury, soft tissue edema, hematoma, and adhesive formations around the plate. Reducing the use of implants is very important, which could avoid mechanical stimulus to the esophagus; furthermore, using a simple operative procedure and reducing the retraction of the esophagus can minimize the occurrence of postoperative dysphagia. Based on the minimally invasive procedure of TSC and the outcome of our results, we recommend the use of TSC for treatment of patients with cervical spondylotic conditions.

One advantage of plate fixation is early mobilization (20). TSC as an external soft collar is used for 3 weeks (one level), 6 weeks (two levels), and 8 weeks (three levels) (21). Our experience indicates that this does not cause the patients any undue discomfort. In fact, they feel psychologically reassured that their necks are being "taken care" of during the postoperative phase. The subaxial cervical spine moves through a lower arc of movement when compared to C0–C2 levels and further degenerative pathology assures global stiffness of the segments being treated; we feel this is sufficient for the early phase of healing. Prospective computational modeling to evaluate stability (that includes the role of neck muscles within collar immobilization) may further elucidate mechanics during TSC.

Fusion is the final aim of treating patients with cervical spondylotic conditions for ACDF or TSC. Previous studies reported similar rates of fusion between both APC and TSC in patients with cervical spondylotic conditions based on different involved levels (e.g., single-level cervical disease vs. multilevel cervical disease) (13), which is consistent with our results. Many issues have affected our results, such as the period of follow-up after surgical treatment, bone quality, different diagnoses of patients, preparation of the endplate for implanting the cage, and distraction achieved by the cage.

Subsidence is also considered the main complication of using the cage for fusion surgery, which has been reported in 9.3%–62.5% of patients with cervical spondylotic conditions (22). This study observed five patients (11.1%) with cage subsidence at the last follow-up. In theory, the subsidence of the cage may cause the disc height and foraminal height changes, which could cause the nerve root or spinal cord compression. The results of our study supported that TSC cannot significantly affect the NRS and NDI between the subsidence and no-subsidence groups. The authors recognize that subsidence is the outcome of numerous factors including bone quality and endplate preparation and may not be a consequence of cage-alone. Delayed union due to bone graft substitute may contribute to the occurrence of subsidence. However, in TSC, the one issue that is eliminated is stress protection afforded by plates and screws that may contribute to delayed union.

Sagittal misalignment as one of the main factors is important for balancing the stress distribution on internal fixation devices and maintaining cervical instability (22). We observed that TSC surgery can maintain cervical lordosis without a significant difference between single- and multilevel disease.

Several methodological issues require consideration. First, a small sample was included in the study. Second, the present study did not include a control group. Further multicenter randomized control trials in assessing TSC vs. APC techniques on the clinical efficacy and consequences of complications for treating patients with cervical spondylotic conditions are required.

Conclusions

Stand-alone cage anterior cervical decompression and fusion surgery is an option for cervical degenerative disc disease of one, two, and three levels. This preliminary report can form the basis for a cost–benefit analysis study either

prospectively or by way of meta-modeling comparing APC, LSC to TSC.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by the Human Research Ethics Committee of the University of New South Wales (NRR-HC210096). The patients/participants provided their written informed consent to participate in this study.

Author contributions

XC, JVC, and ADD contributed to the study concept, design, and data acquisition. XC, AS, and CS contributed to the data analysis and interpretation, drafting of the manuscript, and statistical analysis. AS and ADD revised the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted for the evaluation of Nuvasive cage use for anterior cervical surgery for various indications. The authors declare that the CoRoent Small Contoured peek cage and Maxcess C retractor figures (**Figure 1**) were provided by Nuvasive (Nuvasive, San Diego, CA) for publication.

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References

1. Han SY, Kim HW, Lee CY, Kim HR, Park DH. Stand-alone cages for anterior cervical fusion: are there no problems? *Korean J Spine*. (2016) 13(1):13–9. doi: 10.14245/kjs.2016.13.1.13

2. Mummaneni PV, Kaiser MG, Matz PG, Anderson PA, Groff MW, Heary RF, et al. Cervical surgical techniques for the treatment of cervical spondylotic myelopathy. *J Neurosurg Spine*. (2009) 11(2):130–41. doi: 10.3171/2009.3.SPINE08728

3. Klineberg E. Cervical spondylotic myelopathy: a review of the evidence. *Orthop Clin North Am*. (2010) 41(2):193–202. doi: 10.1016/j.ocl.2009.12.010

4. Song KJ, Taghavi CE, Lee KB, Song JH, Eun JP. The efficacy of plate construct augmentation versus cage alone in anterior cervical fusion. *Spine*. (2009) 34 (26):2886–92. doi: 10.1097/BRS.0b013e3181b64f2c

5. Smith GW, Robinson RA. The treatment of certain cervical-spine disorders by anterior removal of the intervertebral disc and interbody fusion. *J Bone Joint Surg Am*. (1958) 40-A(3):607–24.

6. Pitzen TR, Chrobok J, Stulik J, Ruffing S, Drumm J, Sova L, et al. Implant complications, fusion, loss of lordosis, and outcome after anterior cervical plating with dynamic or rigid plates: two-year results of a multi-centric, randomized, controlled Study. *Spine*. (2009) 34(7):641–6. doi: 10.1097/BRS.0b013e318198ce10

7. He S, Feng H, Lan Z, Lai J, Sun Z, Wang Y, et al. A randomized trial comparing clinical outcomes between zero-profile and traditional multilevel anterior cervical discectomy and fusion surgery for cervical myelopathy. *Spine*. (2018) 43(5):E259–E66. doi: 10.1097/BRS.0000000000002323

8. Liu Y, Wang H, Li X, Chen J, Sun H, Wang G, et al. Comparison of a zero-profile anchored spacer (ROI-C) and the polyetheretherketone (PEEK) cages with an anterior plate in anterior cervical discectomy and fusion for multilevel cervical spondylotic myelopathy. *Eur Spine J*. (2016) 25(6):1881–90. doi: 10.1007/s00586-016-4500-x

9. Stein MI, Nayak AN, Gaskins 3rd RB, Cabezas AF, Santoni BG, Castellvi AE. Biomechanics of an integrated interbody device versus ACDF anterior locking plate in a single-level cervical spine fusion construct. *Spine J*. (2014) 14 (1):128–36. doi: 10.1016/j.spinee.2013.06.088

10. Wang Z, Jiang W, Li X, Wang H, Shi J, Chen J, et al. The application of zero-profile anchored spacer in anterior cervical discectomy and fusion. *Eur Spine J*. (2015) 24(1):148–54. doi: 10.1007/s00586-014-3628-9

11. Zhao Y, Yang S, Huo Y, Li Z, Yang D, Ding W. Locking stand-alone cage versus anterior plate construct in anterior cervical discectomy and fusion: a systematic review and meta-analysis based on randomized controlled trials. *Eur Spine J*. (2020) 29(11):2734–44. doi: 10.1007/s00586-020-06561-x

12. Boer LFR, Zorzetto E, Yeh F, Wajchenberg M, Martins DE. Degenerative cervical disorder-stand-alone cage versus cage and cervical plate: a systematic review. *Global Spine J.* (2021) 11(2):249–55. doi: 10.1177/2192568220906173

13. Chen Y, Lu G, Wang B, Li L, Kuang L. A comparison of anterior cervical discectomy and fusion (ACDF) using self-locking stand-alone polyetheretherketone (PEEK) cage with ACDF using cage and plate in the treatment of three-level cervical degenerative spondylopathy: a retrospective study with 2-year follow-up. *Eur Spine J.* (2016) 25(7):2255–62. doi: 10.1007/s00586-016-4391-x

14. Lee YS, Kim YB, Park SW. Does a zero-profile anchored cage offer additional stabilization as anterior cervical plate? *Spine*. (2015) 40(10):E563–70. doi: 10.1097/BRS.0000000000000864

15. Scheer JK, Tang JA, Smith JS, Acosta Jr. FL, Protopsaltis TS, Blondel B, et al. Cervical spine alignment, sagittal deformity, and clinical implications: a review. *J Neurosurg Spine*. (2013) 19(2):141–59. doi: 10.3171/2013.4.SPINE12838

16. Kao TH, Wu CH, Chou YC, Chen HT, Chen WH, Tsou HK. Risk factors for subsidence in anterior cervical fusion with stand-alone polyetheretherketone (PEEK) cages: a review of 82 cases and 182 levels. *Arch Orthop Trauma Surg.* (2014) 134(10):1343–51. doi: 10.1007/s00402-014-2047-z

17. De Leo-Vargas RA, Munoz-Romero I, Mondragon-Soto MG, Martinez-Anda JJ. Locking stand-alone cage constructs for the treatment of cervical spine degenerative disease. *Asian Spine J.* (2019) 13(4):630–7. doi: 10.31616/asj.2018.0234

18. Gercek E, Arlet V, Delisle J, Marchesi D. Subsidence of stand-alone cervical cages in anterior interbody fusion: warning. *Eur Spine J.* (2003) 12(5):513–6. doi: 10.1007/s00586-003-0539-6

19. Fengbin Y, Xinwei W, Haisong Y, Yu C, Xiaowei L, Deyu C. Dysphagia after anterior cervical discectomy and fusion: a prospective study comparing two anterior surgical approaches. *Eur Spine J.* (2013) 22(5):1147–51. doi: 10.1007/s00586-012-2620-5

20. Binder AI. Cervical spondylosis and neck pain. *Br Med J.* (2007) 334 (7592):527–31. doi: 10.1136/bmj.39127.608299.80

21. Muzin S, Isaac Z, Walker J, Abd OE, Baima J. When should a cervical collar be used to treat neck pain? *Curr Rev Musculoskelet Med.* (2008) 1(2):114–9. doi: 10.1007/s12178-007-9017-9

22. Oh JK, Kim TY, Lee HS, You NK, Choi GH, Yi S, et al. Stand-alone cervical cages versus anterior cervical plate in 2-level cervical anterior interbody fusion patients: clinical outcomes and radiologic changes. *J Spinal Disord Tech.* (2013) 26(8):415–20. doi: 10.1097/BSD.0b013e31824c7d22

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