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New perspectives and innovative techniques in contemporary spine surgery

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New perspectives and innovative techniques in contemporary spine surgery

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Table of contents

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Editorial: New perspectives and innovative techniques in contemporary spine surgery

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Editorial on the Research Topic
New Perspective and Innovative Techniques in Contemporary Spine Surgery

Spine surgery is a multidisciplinary field in which the implementation of novel technologies and techniques has fostered significant advancements in the last decade. The utilization of robotics and navigation systems has made it possible to perform accurate planning and minimize intraoperative complications such as screw malpositioning and increased blood loss (1). Furthermore, the increasing use of microscopy and endoscopy, as well as the integration with both preoperative and intraoperative advanced imaging, is continuously contributing to the development of minimally invasive spine surgery (MISS) techniques (2). Among additional breakthroughs, the use of innovative biofabrication technologies is continuously enhancing the surgeon's armamentarium with different biomaterials and osteobiologics based on diverse clinical needs (3). On the other hand, the application of artificial intelligence (AI) and machine learning (ML) is being extensively employed to develop interactive systems able to support clinical decisions and optimize postoperative outcomes (4–6). Nonetheless, the COVID-19 pandemic has posed unique challenges to the spine community, which have reshaped our practice in several different ways (7).

In this Research Topic, several authors have significantly contributed to providing innovative insights and highlighted the potential of groundbreaking technologies that will likely further advance the field in the next future. Bacco et al. systematically reviewed the available evidence on the application of a novel AI tool, namely, natural language processing (NLP), in spine research. An et al. conducted a retrospective analysis of patients affected by gluteal pain due to lumbar disc herniation (LDH) and treated with percutaneous endoscopic transforaminal discectomy or open discectomy, showing that the former was equally effective while reducing operation time, blood loss, hospital stay, and financial burden. Using a similar study design, Wang et al. evaluated the efficacy of an annulus fibrosus suture device used during endoscopic lumbar discectomy, successfully demonstrating a reduction in the risk of LDH recurrence and no additional complications compared with patients receiving endoscopic discectomy alone. In a single-arm retrospective study, Wang et al. showed that unilateral biportal endoscopic transforaminal lumbar interbody fusion (TLIF) was significantly effective in reducing pain and disability in patients with lumbar spine stenosis, offering intriguing advantages over traditional techniques. In their study, Wu et al. compared the clinical outcomes of patients affected by degenerative spondylolisthesis and treated with oblique lumbar interbody fusion (OLIF) and TLIF, showing lower blood loss, reduced cage subsidence, and increased disc height in the former group. Manufacturing and production of novel osteobiologics to promote bone fusion are crucial for enhancing clinical outcomes following spine surgery. In their study, Aurouer et al. reported successful fusion in >90% of patients undergoing anterior cervical discectomy and fusion and anterior lumbar interbody fusion augmented with supercritical CO_2-processed bone allografts, in the absence of adverse events.

This Research Topic also included reports of unusual cases of spinal disorders and preliminary reports of novel surgical techniques. Ding et al. reported a rare case of spinal involvement in a patient affected by alkaptonuria and severe thoracolumbar stenosis, which was effectively treated with surgical decompression and instrumentation. Meng et al. illustrated a case of severe post-traumatic kyphosis due to an AO type B2.3 T12 fracture successfully treated with posterior hemivertebra resection and segmental fixation. Conversely, Rui et al. compared traditional open pedicle screw fixation for single-level thoracolumbar fractures with percutaneous screw placement augmented with allogeneic bone graft following vertebral body distraction. Intriguingly, this novel technique resulted in lower blood loss, decreased operative time, a reduction of costs, length of stay, and incision length, as well as a higher vertebral height. In their study, Huang et al. described an innovative approach to treat multilevel cervical spondylotic myelopathy based on a modification of the open-door laminoplasty technique, which was performed on alternate sides of the laminae instead of unilaterally. Zou et al. reported the preliminary results of the application of a novel reduction plate specifically manufactured for unstable atlas fractures to be treated via an anterior transoral approach. This surgical approach was also employed by the same authors to develop a novel surgical technique to treat irreducible atlantoaxial dislocations in pediatric patients through intra-articular cage distraction and fusion with a C-JAWS stapler. On the other hand, Miao et al. compared the surgical outcomes of partial C2 laminectomy vs. C2 dome-like laminectomy in patients affected by ossification of the posterior longitudinal ligament, showing that the latter was able to reduce the incidence of neck pain, although the former achieved a wider decompression. In their case series, Xia et al. illustrated a novel technique to treat congenital scoliosis in children aged less than 4 years by means of hemivertebra resection and subsequent prolonged bracing. Although generally feasible and associated with satisfactory outcomes, the authors acknowledged the reduced capacity of this approach to correct thoracolumbar sagittal deformities.

Nonetheless, this Research Topic also included interesting reports on relevant themes in the field of spine surgery. In their study, Lu et al. proposed a modified version of the Thoracolumbar Injury Classification and Severity Score (TLICS). More specifically, the authors suggested implementing an additional subcategory describing the intervertebral disc injury status to underline the importance of the disc complex in vertebral stability. Wang et al. performed a retrospective multicenter review of patients affected by traumatic spinal cord injury in Northwest China. The authors reported an increasing trend of cases in the last few years, followed by a slight reduction due to the COVID-19 pandemic, which provided interesting insights on future strategies to reduce the impact of such a devastating event.

Author contributions

LA, GV, FR, DS, and VD edited the Research Topic and equally contributed to this Editorial. 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.

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ORIGINAL RESEARCH
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A Retrospective Comparative Study of Modified Percutaneous Endoscopic Transforaminal Discectomy and Open Lumbar Discectomy for Gluteal Pain Caused by Lumbar Disc Herniation

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Introduction: This study aimed to demonstrate the safety and effectiveness of modified percutaneous endoscopic transforaminal discectomy (PETD) in the surgical management of single-segment lumbar disc herniation (LDH) gluteal pain and to determine whether it provides a better clinical outcome than open lumbar discectomy (OD).

Methods: A retrospective analysis of patients treated with modified PETD and OD for gluteal pain in LDH from January 2015 to December 2020 was conducted. Sample size was determined using a priori power analysis. Demographic information, surgical outcomes including procedure time (minutes), intraoperative blood loss (mL), hospital days, costs (RMB), fluoroscopy shots, recurrence and complications, etc., were recorded and analyzed. Prognostic outcomes were assessed using the visual analog scale (VAS), the Oswestry Disability Index (ODI), the Japanese Orthopedic Association Score (JOA) and modified MacNab criteria. The preoperative and postoperative VAS, ODI and JOA scores were recorded by two assistants. When the results were inconsistent, the scores were recorded again by the lead professor until all scores were consistently recorded in the data. MRI was used to assess radiological improvement and all patients received follow-ups for at least one year.

Results: The sample size required for the study was calculated by a priori analysis, and a total of 72 participants were required for the study to achieve 95% statistical test power. A total of 93 patients were included, 47 of whom underwent modified PETD, and 46 of whom underwent OD. In the modified PETD intragroup comparison, VAS scores ranged from 7.14 ± 0.89 preoperatively to 2.00 ± 0.58, 2.68 ± 0.70, 2.55 ± 0.69, 2.23 ± 0.81, and 1.85 ± 0.72 at 7 days, 1 month, 3 months, 6 months, and 12 months postoperatively. Patients showed significant pain relief postoperatively ($P < 0.01$). According to the modified MacNab score, the excellent rate in the PETD group was 89.36%. There was no significant difference compared to the OD group (89.13%,

$P > 0.05$). Complication rates were lower ($P > 0.05$) but recurrence rates were higher ($P > 0.05$) in the modified PETD group than in the OD group. The modified PETD group had a faster operative time ($P < 0.01$), shorter hospital stay ($P < 0.01$), less intraoperative bleeding ($P < 0.01$), and less financial burden to the patient ($P < 0.01$) than the OD group. At 7 days postoperatively, the VAS score for low back pain was higher in the OD group than in the modified PETD group ($P < 0.01$). The VAS and JOA scores at 1, 3, 6, and 12 months postoperatively were not significantly different between the modified PETD and OD groups ($P > 0.05$), and the ODI was significantly different at 3 months postoperatively ($P < 0.05$).

Conclusion: Modified PETD treatment is safe and effective for gluteal pain due to L4/5 disc herniation and has the advantages of a lower complication rate, faster postoperative recovery, shorter length of stay, fewer anesthesia risks and lower cost of the procedure compared with OD. However, modified PETD has a higher recurrence rate.

Keywords: lumbar disc herniation, gluteal pain, percutaneous endoscopic transforaminal discectomy, open lumbar discectomy, minimally invasive surgery

INTRODUCTION

Lumbar disc herniation (LDH) is one of the most common degenerative diseases of the lumbar spine, typically causing lower back pain and sciatica (1, 2). Gluteal pain has often been a clinical manifestation, and sometimes the only manifestation, of patients with LDH (3).

In a retrospective study reported by Fang et al. (3), 94.64% of patients with gluteal pain had responsible L4/5 segments ($P < 0.001$), and 5.36% had L5/S1. Wang et al. (4) subsequently described the mechanism of gluteal pain in LDH and suggested that it may be related to the superior and inferior gluteal nerves. All the fibers of the anterior branch of the L5 nerve root form the lumbosacral trunk, which forms part of the sacral plexus and branches distally into the superior gluteal nerve (L4, L5, S1) and the inferior gluteal nerve (L5, S1, S2), innervating the sensory muscles of the gluteal region, respectively (5, 6). In addition, compression of the posterior branch of the spinal nerve may contribute to gluteal pain, as the anterior and posterior roots merge at the intervertebral foramen to form the spinal nerve, which immediately divides into the posterior branch, creating a thicker nerve trunk that includes the superior cluneal nerves. Previous studies (7, 8) have shown that in addition to L1, L2, and L3, the posterior branches of the L4 and L5 spinal nerves are also involved in the formation of the superior cluneal nerves. Further autopsies have confirmed that approximately 10% of the superior cluneal nerves originate from L5 (9), a group of purely sensory nerve fibers controlling the gluteal region (10, 11). This reveals a strong correlation between gluteal pain and L4/5 disc herniation.

In terms of surgical treatment, OD remains the standard of care for pain secondary to LDH (12, 13), which is performed via a posterior approach, where the epidural space is exposed in the posterior midline by separating the paravertebral muscles as well as excising the lamina and ligamentum flavum. The herniated disc is removed after excision of a section of the facet joint on the symptomatic side while protecting the spinal cord and nerve roots (14). Although OD is effective, it can also cause considerable tissue damage (15).

With the development of minimally invasive methods, PETD is rapidly replacing OD in procedures requiring discectomy and decompression (16). Experienced surgeons can reach the lesion directly through Kambin's triangle bypass (17). PETD avoids extensive damage to the skin, muscles, laminae, and synapses (18), and more significantly, excessive strain on the dural sac is avoided (19). Li et al. (14) also demonstrated that PETD achieved satisfactory results in the treatment of LDH with a reduced incidence of iatrogenic injury and minimal activity restrictions compared to OD, thus accelerating rapid recovery.

However, PETD focuses on the surgical approach and removal of the nucleus pulposus. The annulus fibrous and posterior longitudinal ligament, which may cause gluteal pain, are not treated or described in detail (20). Therefore, this study investigated a modified PETD that hypothesized that resection of the annulus fibrosus and posterior longitudinal ligament might significantly reduce pain in patients. The purpose of this study was to assess the safety and efficacy of a modified PETD compared with OD for treating L4/5 single-segment disc herniation.

MATERIALS AND METHODS

Patients

The clinical study was approved by the Chinese Ethics Committee (No. 2021001). We recruited patients who underwent either the modified PETD technique or OD patients for LDH at our institution from January 2015 to November 2020 and were followed up for at least one year. Telephone follow-ups were carried out at each follow-up time, and basic information about all patients was reviewed. In addition, patients were invited to undergo reexamination to observe their most recent clinical and radiological results.

The inclusion criteria were adult patients with single-segment L4/5 disc herniation with only symptoms of gluteal pain. Patients chose to be treated with either a modified PETD technique or OD. The exclusion criteria were as follows: a previous history of lumbar operation; missed visits within one year or recurrence within the follow-up period; multisegment lumbar degenerative disease; and severe peripheral nerve disease (**Figure 1**). Recurrence was defined as a recurrence of the same level of disc herniation, and reoperation was performed.

Preoperative

All patients underwent preoperative magnetic resonance imaging (MRI) of the lumbar spine, computed tomography (CT), and lumbar X-ray plain radiographs (anterior and lateral views). The same physician treated all patients. The modified PETD technique was performed using local anesthesia, and patients were informed of the potential for intraoperative discomfort and pain. A transilluminated surgical bed and C-arm were used for intraoperative positioning. Normal saline (3,000 mL) was used for continuous irrigation via the endoscope.

Operative

The routine procedure was as described in a previous study (21). In brief, the patient was operated on in a lateral position with the affected side facing upward and a soft cushion on the lumbar area. The skin entry point was above the iliac crest, 12–14 cm from the midline. After local anesthesia, the superior articular eminence of the external L5 was fixed under C-arm guidance and infiltrated locally with additional anesthetic. A guidewire was inserted through an 18-gauge needle, and an incision of approximately 0.7 cm was made at the edge of the guidewire. A stepwise dilating catheter was placed along the guidewire to bluntly separate the surrounding muscle tissue, place a working channel and connect to the endoscopic system. Physiological saline was continuously

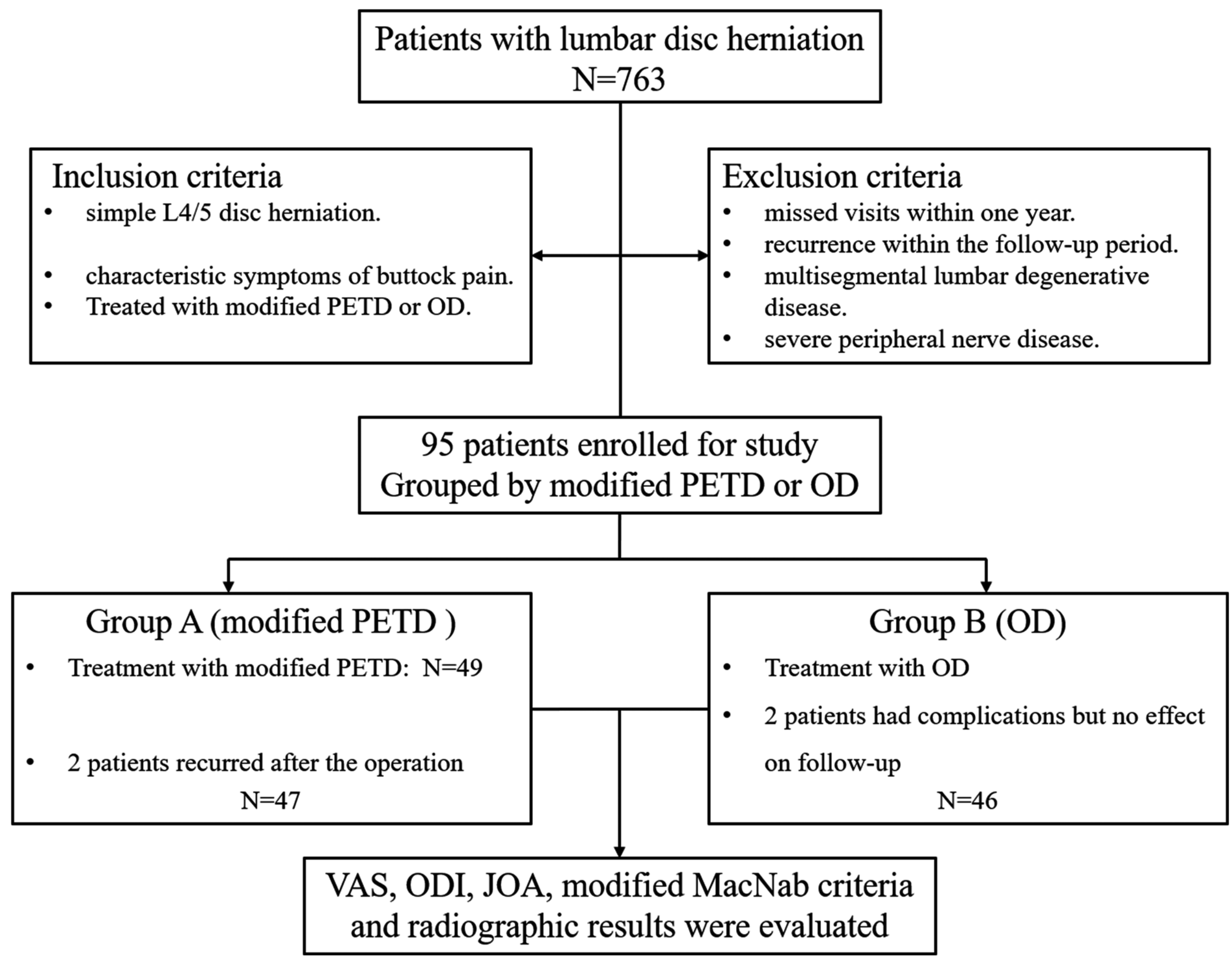

FIGURE 1 | Flow chart of patient inclusion and stratification. Modified PETD, modified percutaneous endoscopic transforaminal discectomy; OD, open lumbar discectomy.

irrigated to ensure a clear view, and the protruding nucleus pulposus was removed using endoscopic forceps.

Denervation of the Annulus Fibrous

After visualization of the symptomatic lateral annulus fibrous in endoscopic view, denervation of the annulus fibrosus was performed starting from the posterior longitudinal ligament at the posterior edge of the vertebral body up to the pediculus arcus vertebrae, with emphasis on radiofrequency ablation of the ruptured end of the annulus fibrosus. The proliferating nerves and vessels were eliminated (**Figure 2**).

Excision of Hypertrophic Annulus Fibrous and Posterior Longitudinal Ligaments

After denervation, the hypertrophied annulus fibrous and posterior longitudinal ligament at the superior margin of the symptomatic inferior vertebral body was removed. The posterior longitudinal ligament was removed with endoscopic forceps (**Figure 3A**).

Lateral Recess Decompression

An endoscopic circular saw and osteotome were used to remove the hyperplastic superior facet joint up to the superior edge of the vertebral arch. A portion of the ligamentum flavum was removed to completely decompress the "peripheral recess" (**Figure 3B**). The endoscopic view showed good nerve root pulsation and complete decompression. Fluid gelatin was injected before removing the working cannula to prevent hematoma, and finally, the wound was sutured. A preoperative and postoperative MRI comparison showed complete removal of the nucleus pulposus and decompression of the lateral saphenous fossa (**Figure 4**).

Clinical Assessment

Demographic information included age, sex, body mass index (BMI), smoking habit, alcohol consumption, hypertension, diabetes, duration of symptoms, side of symptoms, and follow-up time. Surgical outcomes included the duration of surgery, intraoperative blood loss, length of hospital stay, cost of surgery, number of radiation sessions, recurrence, and complications. Recurrence was defined as a reherniation of the disc at the same segment and on the same side with a VAS score >4. The prognostic outcome was assessed by the outcome values and improvement rates of VAS, ODI, JOA, and the modified MacNab criteria, where the primary outcomes are the outcome values and the improvement rates

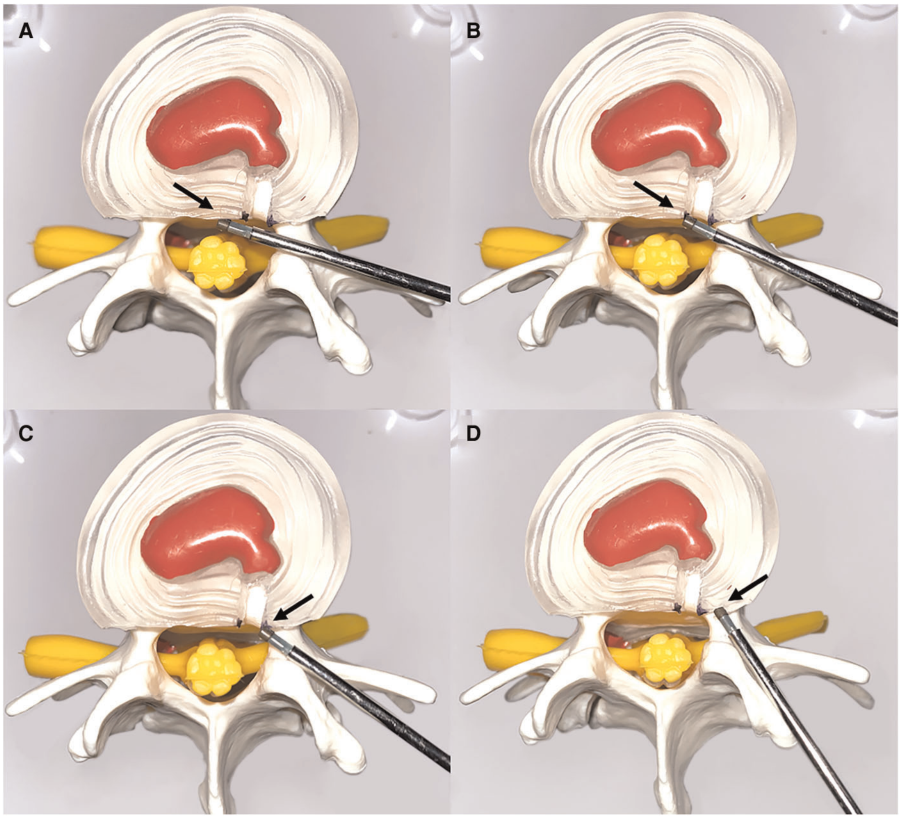

FIGURE 2 | Schematic representation of the denervation of an annulus fibrosus. (**A**) Denervation from the posterior longitudinal ligament (black arrow). (**B,C**) Focused treatment of radiofrequency ablation of an annulus fibrosus dissection (black arrow). (**D**) Final denervation of the annulus fibrosus superior to the vertebral arch (black arrow).

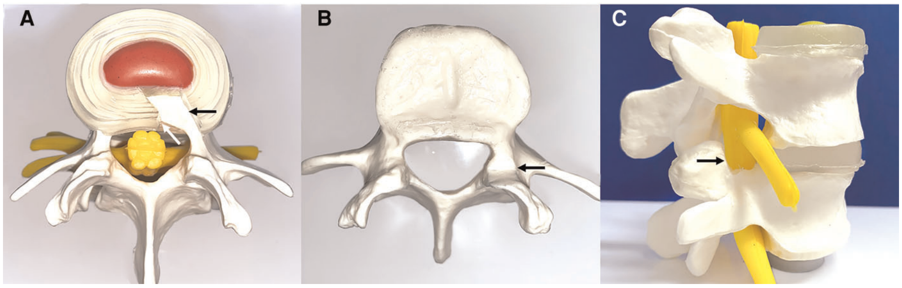

FIGURE 3 | Schematic diagram of annulus fibrosus excision and lateral recess decompression. (**A**) Excision of the hypertrophic annulus fibrosus (black arrow) and posterior longitudinal ligament (white arrow). (**B,C**) Transverse and sagittal demonstration of lateral recess decompression with partial resection of the superior facet joint (black arrow).

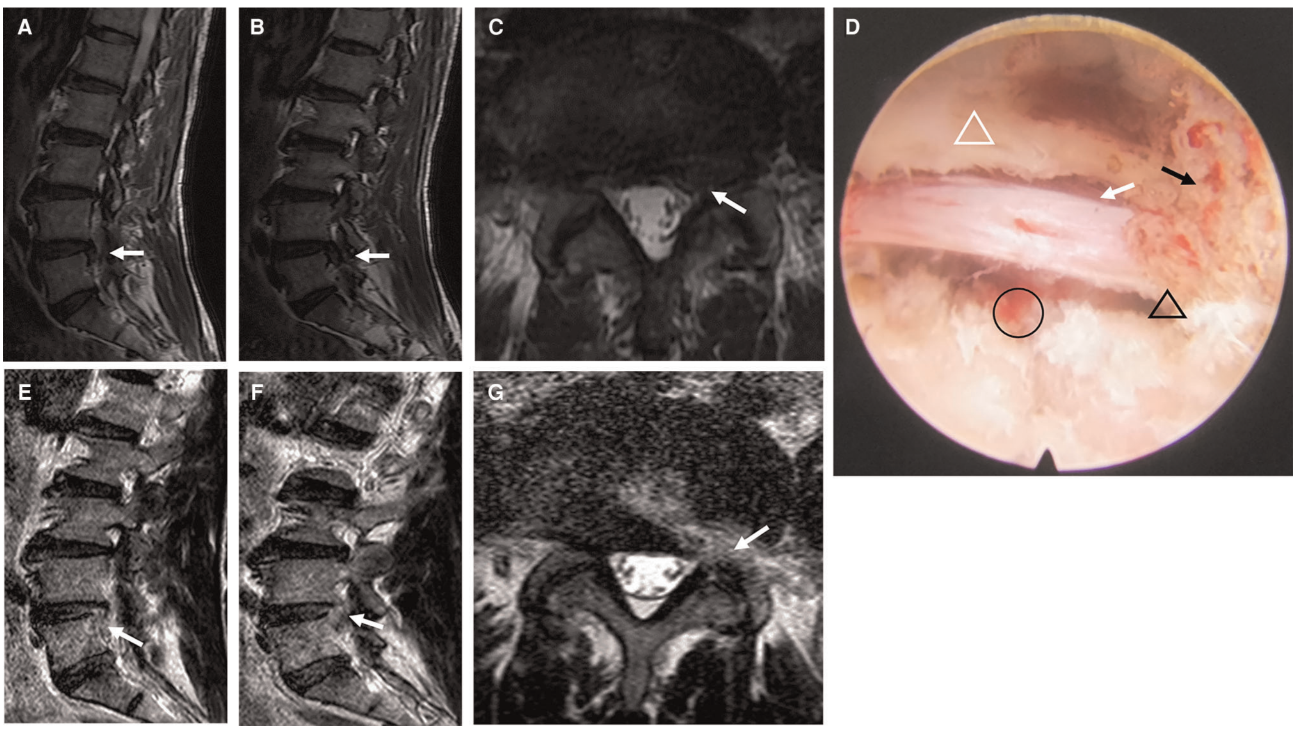

FIGURE 4 | Pre- and postoperative images and intraoperative microscopic images of modified PETD. (**A–C**) Preoperative MRI demonstrated lumbar disc herniation (white arrows). (**D**) A completely decompressed nerve root is visible endoscopically (white arrow), with removal of the fibrous annulus (black circle), decompression of the lateral recess (black triangle), facet joint resection (black arrow), and partial ligamentum flavum resection (white triangle). After modified PETD, (**E,F**), the fibrous ring at the superior margin of the inferior conus was removed, and lateral saphenous fossa decompression was performed (**G**) (white arrow).

of VAS. The improvement rates for VAS and ODI were calculated using the (preoperative-postoperative)/preoperative formula for the results and the (postoperative-preoperative)/(29-preoperation) formula for JOA. The VAS is a subjective numerical pain scale that assesses the gluteal pain experienced by the patient in the last 24 h. The ODI, JOA and modified MacNab criteria are used to measure the degree of disability and treatment for the life of patients with gluteal pain, reflecting the recovery of function and the ability of patients to manage daily life after surgery (22).

Statistical Analysis

We used G-POWER Analysis (Version 3.1.9.7) (23, 24) to obtain the minimum sample size required to achieve a medium effect (effect size, $d = 0.25$), a power of 95%, and a statistical significance level of 0.05. To achieve statistical significance, we found that at least 72 samples were required. IBM SPSS Statistics (version 23.0) was used for data analysis. The data are expressed as the mean ± standard deviation (SD) and frequency (percentage). The two groups were compared using Pearson chi-square tests or Fisher exact tests for categorical variables and independent samples t tests or Mann–Whitney tests for continuous variables. Outcome values and improvement rates for VAS, ODI, JOA and excellent rates for modified MacNab criteria were compared between groups using multivariate analysis. Modified PETD intragroup comparisons were performed using two-way repeated-measures ANOVA. *P* values <0.05 were considered statistically significant. All graphs were constructed with GraphPad Prism (version 8.0.2).

RESULT

Demographic Information and Surgical Outcomes

The results of the a priori power analysis indicated that the study required at least 72 subjects. A total of 93 participants eventually met the inclusion criteria, of whom 49 opted for the modified PETD technique and 46 patients for OD. All participants had unilateral gluteal pain, and the type of LDH was paramedian. The mean follow-up times were 15.98 ± 4.23 and 16.11 ± 4.32 months for the modified PETD and OD groups, respectively. Demographic information, including age, sex, BMI smoking, alcohol, hypertension, diabetes, duration of symptoms, side of symptoms and follow-up time, were not significantly different between the two groups ($P > 0.05$). Compared to the OD group, the modified PETD group had a significantly shorter operative time ($P < 0.01$), less intraoperative bleeding ($P < 0.01$), and a shorter hospital stay ($P < 0.01$). In addition, the modified PETD technique imposed a smaller financial burden on the patient ($P < 0.01$). However, there were fewer fluoroscopic shots in the OD group ($P < 0.01$) (**Table 1**).

TABLE 1 | Demographic information and Surgical outcomes.

Characteristic	Modified PETD	OD	*P*-Value
Number (No.)	49	46	
Age (Yrs)	52.98 ± 11.52	52.98 ± 10.48	0.843
Gender (M:F)	23:26	21:25	0.900
BMI	24.93 ± 2.46	24.14 ± 3.32	0.190
Smoking (Y)	43%	41%	0.878
Alcohol (Y)	39%	41%	0.648
Hypertension (Y)	29%	28%	0.973
Diabetes (Y)	18%	17%	0.682
Duration of symptom (Mos.)	4.53 ± 1.54	4.48 ± 1.39	0.863
Side of symptoms (L:R)	23:26	22:24	0.350
Follow-up times (Mos.)	15.98 ± 4.23	16.11 ± 4.32	0.974
Duration of operation (min)	65.25 ± 8.37	127.72 ± 13.47	<0.01*
Blood loss (mL)	32.08 ± 4.79	126.26 ± 6.36	<0.01*
Hospital stays (day)	3.00 ± 0.35	7.11 ± 1.23	<0.01*
Costs (RMB)	3.55 [3.30, 3.80]	6.18 [5.78, 6.50]	<0.01*
Fluoroscopy shots	6.37 ± 0.86	3.59 ± 0.83	<0.01*
Recurrence	4%	0%	0.495
complications	0%	4%	0.232

Patients are classified according to different surgical procedures. Data are presented as the mean ± standard deviation or number (%).
No., number; Yrs, years; M, male; F, female; Y, yes; Mos., months; L, left; R, right.
**Significant difference between the two groups (P < 0.05).*

Prognostic Outcomes

All patients were interviewed by telephone at 1 month, 3 months, 6 months, and 12 months after the operation. The results showed that the VAS score outcome values decreased from 7.14 preoperatively to 2.00, 2.68, 2.55, 2.23, and 1.85 at 7 days, 1 month, 3 months, 6 months and 12 months postoperatively in the modified PETD group, with significant differences at each follow-up time compared with preoperatively ($P < 0.01$). Comparing between groups, the VAS score outcome value of 1.61 for gluteal pain at 7 days postoperatively in the OD group was better than that of 2.00 in the modified PETD group ($P < 0.05$) (**Figure 5A**), but the VAS score outcome value of 1.53 for low back pain (caused by surgical incision) at 7 days postoperatively in the modified PETD group was less severe compared to 2.70 in the OD group ($P < 0.05$) (**Figure 5B**). The improvement rates of VAS scores in the modified PETD group were 61.77%, 63.41%, 67.85%, and 73.47% at 1, 3, 6, and 12 months postoperatively, respectively. There was no significant difference compared to the OD group ($P > 0.05$) (**Figure 5C**). Within-group comparisons of the modified PETD group, the preoperative and postoperative outcome values for ODI (**Figure 6A**) and JOA (**Figure 6C**) showed dramatic improvements in both symptoms and function ($P < 0.05$). Compared with the OD group, the improvement rate of the ODI was statistically significant ($P < 0.05$) at 3 months postoperatively (**Figure 6B**), and there was no statistically significant ($P > 0.05$) improvement of the JOA during the follow-up period (**Figure 6D**).

According to the modified MacNab criteria, 33 (70.21%) and 9 patients (19.15%) in the modified PETD group were considered "excellent" and "good" at 12 months postoperatively (**Figure 7A**), respectively; similarly, 33 (71.74%) and 8 patients (17.39%) in the OD group were considered "excellent" and "good,", respectively (**Figure 7B**). Comparisons between groups were not statistically significant ($P > 0.05$).

Recurrence and Complications

In the modified PETD group, two patients presented with recurrence at 15 days and 21 days postoperatively. We then treated them with OD, and the prognosis was favorable. Two patients in the OD group developed complications, a cerebrospinal fluid (CSF) leak and a hematoma. The former underwent intraoperative dural suturing and returned to the ward in a decubitus position for 12 h, where the headache caused by the CSF leak was relieved 5 days postoperatively. The latter presented with neurological compression due to a hematoma and recovered well after emergency debridement (**Table 2**).

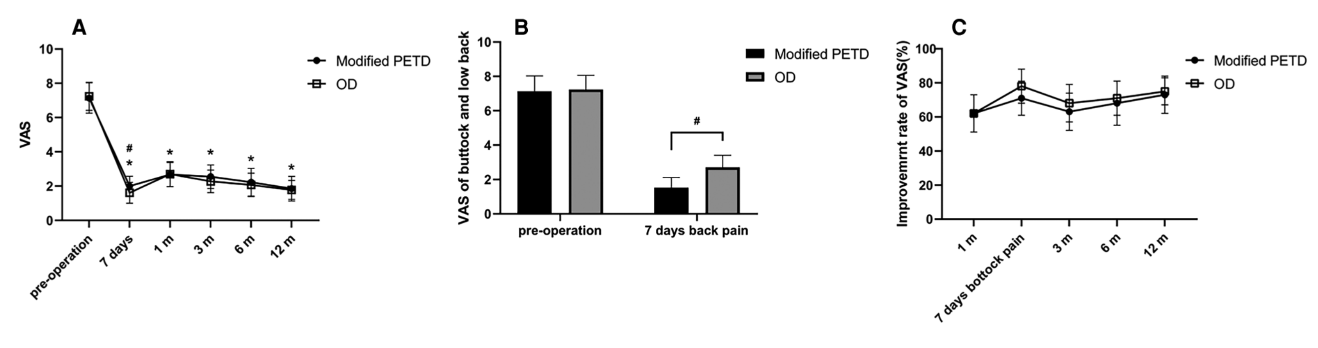

FIGURE 5 | VAS score outcome values (**A**), VAS score outcome values for low back pain at 7 days postoperatively (**B**), and VAS score improvement rate (**C**). * indicates statistical significance compared within groups ($P < 0.01$), # indicates statistical significance compared between groups ($P < 0.05$).

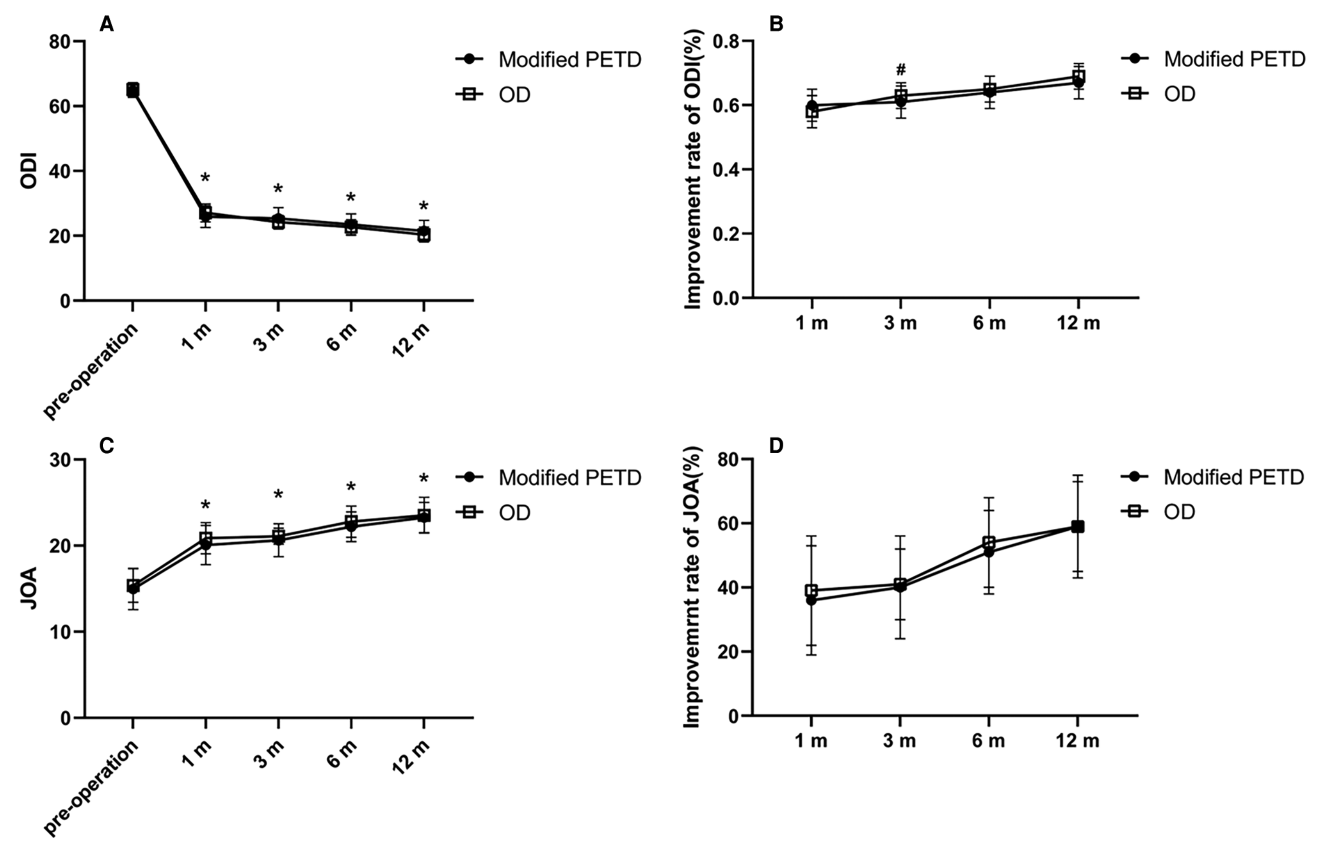

FIGURE 6 | Outcome values (**A**) and improvement rates (**B**) for the ODI. Outcome values (**C**) and improvement rates (**D**) for the JOA. * indicates statistical significance compared within groups ($P < 0.01$). # indicates statistical significance compared between groups ($P < 0.05$).

DISCUSSION

Current Status of PETD Research

With the development of endoscopic techniques, surgeons have become more experienced, and patients prefer minimally invasive surgery, resulting in the rapid development of minimally invasive procedures for the spine (25). PETD has become the most used minimally invasive technique in recent decades due to its small incision, minimal damage to muscle and soft tissue structures, and minimal postoperative epidural fibrosis (20, 26).

It is generally accepted that PETD appears to be indicated for all types of LDH (27, 28). However, an RCT by Chen et al. (29) showed that PETD is more suitable for treating paracentral

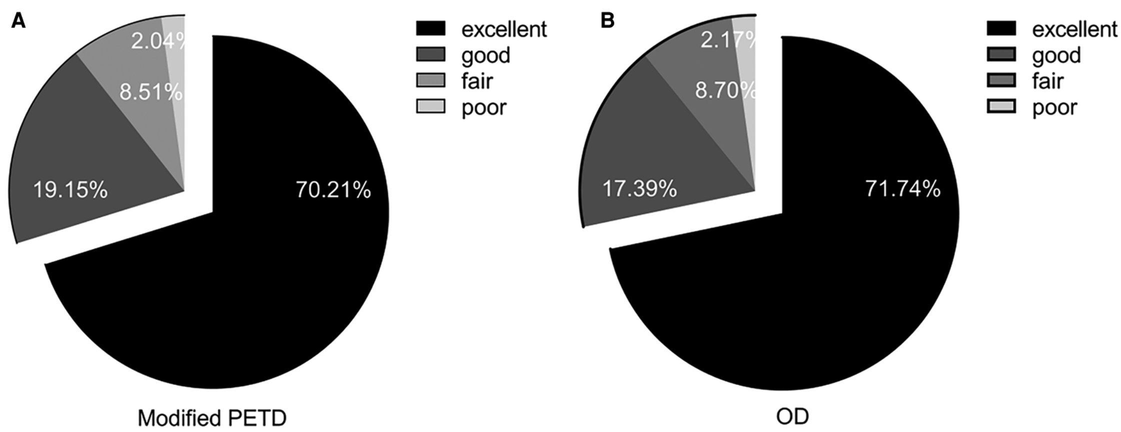

FIGURE 7 | Modified MacNab scores for the modified PETD group (**A**) and for the OD group (**B**) at the postoperative follow-up at 12 months.

TABLE 2 | Recurrence and complications.

	No.	Age	Gender	BMI	Diagnosis	OP level	Recurrence days	Treatment
Modified PETD	1	47	Male	28.0	Recurrence	L4/5	11	OD
	2	45	Male	26.5	Recurrence	L4/5	16	OD
OD	1	72	Female	23.4	CSF leak	L4/5	–	Dural suture
	2	64	Female	25.2	Hematoma	L4/5	–	Debridement

Different surgical approaches leading to recurrence and complications.
No., number CSF, cerebrospinal fluid.

herniations, where a transforaminal approach facilitates visualization of the lesion. For median-type herniations, the limitations of the intervertebral foramen and dura lead to poorer clinical outcomes. This provides theoretical support for our study. All patients with gluteal pain had unilateral nerve root compression in the present study. Furthermore, the absence of iliac crest obstruction at the L4/5 level makes PETD a great advantage in the treatment of gluteal pain. However, PETD focuses on the surgical approach and removal of the nucleus pulposus and does not address or describe the annulus fibrous and posterior longitudinal ligament (20).

Theoretical Basis for the Modification of the PETD

During clinical procedures, we found that stimulation of the patient's fibrous annulus and posterior longitudinal ligament induced symptoms of gluteal pain. The patient showed considerable relief after denervation and removal of the fibrous annulus and posterior longitudinal ligament on the symptomatic side. Li et al. (30) showed that the sinus vertebral nerve (SVN) was divided into two types, the SVN deputy branch (type I) and the SVN main trunk (type II), with the SVN deputy branch entering the posterior lateral border of the disc and the SVN main trunk originating from the spinal ganglion and connecting to the sympathetic nerve via a traffic branch. Seventy (22.44%) SVN deputy branches and 23 (21.74%) SVN main trunks were found in the L4/5 intervertebral foramen. According to R et al. (31), part of the ascending branch of the SVN originates in the posterior longitudinal ligament, and microscopic observation of the sensory fibers of the posterior longitudinal ligament revealed that it receives a large number of traffic fibers of the SVN and forms a fiber network (32). When LDH is present, the production of inflammatory mediators leads to the transmission of inflammatory cytokines that hypersensitize SVN terminal receptors (33), which reduces the pain threshold and triggers buttock pain (34). Therefore, we hypothesized that gluteal pain might be associated with both and made improvements to the original.

Modified PETD Has Great Potential to Treat Gluteal Pain Caused by L4/5 Disc Herniation

The modified PETD is safe and effective for treating gluteal pain caused by L4/5 disc herniation. The results showed that patients treated with the modified PETD showed a significant improvement postoperatively compared to preoperatively ($P < 0.01$). According to the modified MacNab score, 89.36% of patients were satisfied with the outcome 12 months after the procedure. There were no statistically significant differences in the VAS and JOA assessments of patients at 1, 3, 6, and 12 months after the modified PETD compared to those of the OD group ($P > 0.05$). The ODI was statistically significant only at 3 months postoperatively ($P < 0.05$), which we believe may be related to the subjective nature of the rating scale. In addition, there were no complications after treatment in the modified PETD group, although two patients experienced recurrence (4%), which we speculate may be related to the removal of the annulus fibrous tissue. Further studies are needed to determine whether the removal of the nucleus pulposus should be expanded. In summary, the modified PETD provides direct access to the lesion, relieves compression, and provides effective radiofrequency ablation of the SVN on the annulus fibrosus and posterior longitudinal ligament, relieving the patient's symptoms. In addition, decompression of the lateral recess can also be accomplished with good results with modified PETD using a circular saw and a high-speed drill (35). The potential of the modified PETD for the treatment of LDH for gluteal pain was revealed.

Comparison Between Modified PETD and OD

For patients with LDH with severe ossification or severe lumbar spinal stenosis, OD is an excellent treatment option. Complete extraction of the nucleus pulposus considerably reduces the possibility of recurrence. Furthermore, the adverse effects of recurrence should also be considered. A study by K et al. (36) showed that the reoperation rate of minimally invasive surgery patients was 3.1% higher than that of open surgery patients and that reoperation not only has negative psychological and physical impacts on the patients but also increases their financial burden. Nevertheless, due to the greater invasiveness, the patient has a longer recovery time and must endure the pain of a large incision (37), which can fail to heal in some diabetic patients. In addition, fixation of the nail bar system accelerates the degeneration of adjacent segments (38, 39). More importantly, when open surgery is performed, in addition to the removal of the lamina, the medial articular processes may be removed, and the surrounding ligament system and muscles may be destroyed. Extensive disruption of the posterior column may increase the risk of lumbar kyphosis (40) and lumbar spondylolisthesis (41). PETD avoids damage to the vertebral plates and spinous processes and greatly reduces the incidence of retroflection deformities (42). G et al. (43) showed no difference between PETD and OD for medium- to long-term pain and functional status. This is consistent with the results of our study. Similarly, this suggests that the two surgical strategies have the same efficacy. In addition, the modified PETD group had less postoperative low back pain ($P < 0.01$) and fewer complications than the OD group. For elderly patients with comorbidities, we should avoid the risks associated with general anesthesia and opt for safer local anesthesia (44). More importantly, for single-segment LDH, the modified PETD procedure appears to offer more benefit to patients than OD.

Differential Diagnosis Related to Gluteal Pain

Buttock pain is often not a typical symptom of LDH. In clinical practice, it is often difficult for physicians to connect them, resulting in misdiagnosis and a delay in optimal treatment. Conditions that can cause buttock pain include deep gluteal syndrome and pain caused by the facet joint or sacroiliac joint (4, 45, 46). Deep gluteal syndromes are sciatica of nondiscogenic origin (47), including piriformis syndrome, gemelli-obturator internus syndrome, and ischiofemoral impingement syndrome (48). According to the literature by H et al. (49), the most common clinical feature of deep gluteal syndrome is pain in the buttocks, which is aggravated by prolonged sitting. In some patients, the straight leg raising test may be positive. These symptoms can be easily confused with the symptoms of buttock pain caused by LDH. Therefore, an accurate diagnosis of the disease before the operation is essential. In addition to a careful physical examination and empirical diagnosis, the surgeon should determine whether the patient's symptoms are related to the lumbar spine by visualizing the MRI with the support of a radiological examination.

Limitations

While this was a good retrospective study, there are still some limitations of which to be aware. A significant limitation is the retrospective nature of the study. The decision on surgical strategy was based on patient preferences. Second, the study population included only 93 patients from one hospital, which may have biased the results to some extent. Another is that this study reviewed patients with single-segment L4/5 disc herniations, and further research is still needed to determine the applicability of the modified PETD technique in patients with other segmental disc herniations. Third, further research is still required to explore the necessity of extended disc removal and preventing postoperative recurrence. Finally, when calculating the cost, we only counted the cost of minimally invasive surgery and not the cost of other procedures due to recurrence, which may lead to bias.

CONCLUSIONS

The symptoms of gluteal pain due to L4/5 disc herniation should be highlighted in clinical practice. Modified PETD treatment is safe and effective and has the advantages of a lower complication rate, faster postoperative recovery, shorter length of stay, fewer anesthesia risks and lower cost of the procedure compared with OD. However, modified PETD has a higher recurrence rate, and reoperation caused by recurrence may increase the financial burden.

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

The studies involving human participants were reviewed and approved by the second hospital of Jilin university. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

JYA, JPW, TH, ZHY, RL, WX and LQ collected data. JYA prepared the manuscript with important intellectual input from all authors. JZ and TY verified the analytical methods and performed statistical analysis. QYL and YZL performed a final review of the manuscript. All authors approved the final manuscript. All authors contributed to the article and approved the submitted version.

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Natural language processing in low back pain and spine diseases: A systematic review

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Natural Language Processing (NLP) is a discipline at the intersection between Computer Science (CS), Artificial Intelligence (AI), and Linguistics that leverages unstructured human-interpretable (natural) language text. In recent years, it gained momentum also in health-related applications and research. Although preliminary, studies concerning Low Back Pain (LBP) and other related spine disorders with relevant applications of NLP methodologies have been reported in the literature over the last few years. It motivated us to systematically review the literature comprised of two major public databases, PubMed and Scopus. To do so, we first formulated our research question following the PICO guidelines. Then, we followed a PRISMA-like protocol by performing a search query including terminologies of both technical (e.g., *natural language* and *computational linguistics*) and clinical (e.g., *lumbar* and *spine surgery*) domains. We collected 221 non-duplicated studies, 16 of which were eligible for our analysis. In this work, we present these studies divided into sub-categories, from both tasks and exploited models' points of view. Furthermore, we report a detailed description of techniques used to extract and process textual features and the several evaluation metrics used to assess the performance of the NLP models. However, what is clear from our analysis is that additional studies on larger datasets are needed to better define the role of NLP in the care of patients with spinal disorders.

KEYWORDS

natural language processing, deep learning, low back pain, spine disorders, artificial intelligence, systematic review

1. Introduction

Low Back Pain (LBP) is a particular condition of "pain and discomfort localized below the costal margin and above the inferior gluteal folds, with or without leg pain" as defined in the European Guidelines for Prevention of Low Back Pain [1]. Based on the onset, such condition may be either classified as acute or chronic. Events of the former category usually occur suddenly, lasting no more than six weeks, often associated with trauma. We refer to chronic LBP if the pain lasts more than twelve weeks, caused by a large pool of diseases like disc degeneration and herniation, spondyloarthritis and spondylolisthesis. In many cases, chronic LBP is treated with spine surgery, involving several risks for the patient, including persisting pain, incidental dural tears, vascular injuries, and infections.

The prevalence of such a musculoskeletal condition is increasing world-wide. A recent study [2] has reported the number of people experiencing LBP at some point in their lives increased from 377.5 million in 1990 to 577.0 million in 2017, globally. Even if the prevalence increases with age, a large amount of people experiences LBP not only in their earlier adulthood but also during adolescence [3]. In particular, chronic LBP is often considered the main reason for disability in a large portion of the population [4]. Even in cases in which pain does not imply disability, this condition often causes activity limitation and work absence [5,6], leading to a high economic burden on workers, industries, and governments [7]. All these aspects concerning LBP and, more in general, related spine disorders, pose a particular attention towards the care of this condition.

In recent years, the most ground-breaking technologies have been explored in the care of LBP, including Artificial Intelligence (AI) and Computer Science (CS), which have seen their application in the care of LBP in several studies [8,9]. A promising trend in this field involves Natural Language Processing (NLP), a discipline at the intersection between CS, AI, and Linguistics. NLP leverages unstructured texts written in the human-interpretable (natural) language. In recent years, NLP has already been applied in health-related domains, from radiology [10] to oncology [11], ranging from health-specific tasks, such as classifying medical notes from the clinical notes [12], to more traditional ones, such as opinion mining on patients' reviews [13]. Recently, another review has focused on NLP in chronic diseases [14] in which, differently from our work, the authors did not focus on any spine disorder. However, the combination of NLP and healthcare is progressively gaining momentum, and has also been investigated in LBP care models. In this study, we have systematically reviewed the available literature on the application of NLP to develop innovative tools for diagnosing and treating LBP. Our aim is to describe the state of the art of such technology and identify future directions and potential implementations.

2. Materials and methods

To perform an exhaustive overview of the applications of NLP in the management of LBP we interrogated both PubMed and Scopus databases with similar queries. For both databases, we performed the search on November 6th, 2021.

2.1. Research question

AI and CS systems have already been shown to be a great support to physicians in the task of diagnosing and treating LBP and related pathologies in humans [8,9]. With this work, we aimed to provide a comprehensive review of the literature regarding the described applications of NLP-related methods to the care of patients affected by LBP. Precisely, following the *PICO* guidelines, we aimed to answer the following research question:

- In human subjects, no matter for any demographic information, affected by LBP and related spine disorders {**P**opulation/**P**roblem}
- may NLP-related methodologies, {**I**ntervention}
- compared with human operators and already existing tools, {**C**omparison}
- help healthcare providers in the management of such conditions? {**O**utcome}

2.2. Research protocol

To perform an exhausting review of the literature, we developed the following research protocol. First of all, we elaborated a search query. Then, we formalized the inclusion/exclusion criteria. We performed the query on two public databases, namely PubMed and Scopus. In both databases, we performed the query on the title and the abstract of the articles. For the Scopus database, in addition, we also considered the keywords assigned to the papers. After conducting the first screening by removing the duplicated articles, two authors carried a preliminary screening after reviewing titles and abstracts (and, eventually, the keywords) of the total amount of papers. After that, the same authors went deeper by analyzing full-text articles. During the previous steps, we excluded papers not meeting the inclusion criteria from further analyses. Whenever a discordance happened, the two authors discussed it together until reaching a consensus. Finally, we reported in the present review the works retrieved.

The developed protocol is resumed in **Figure 1**, reporting the flow-chart diagram realized according to the *PRISMA* protocol.

2.3. Search query

The proposed search query was divided into two different parts, one including terms from the NLP terminology, the other including terms related to LBP. In each of the two query sections, the terms have been linked by the logical OR operation, while the inter-relation between the two parts has been represented by the logical AND operation, meaning that the papers resulting from the interrogation had to present at least one of the terms for both query sections.

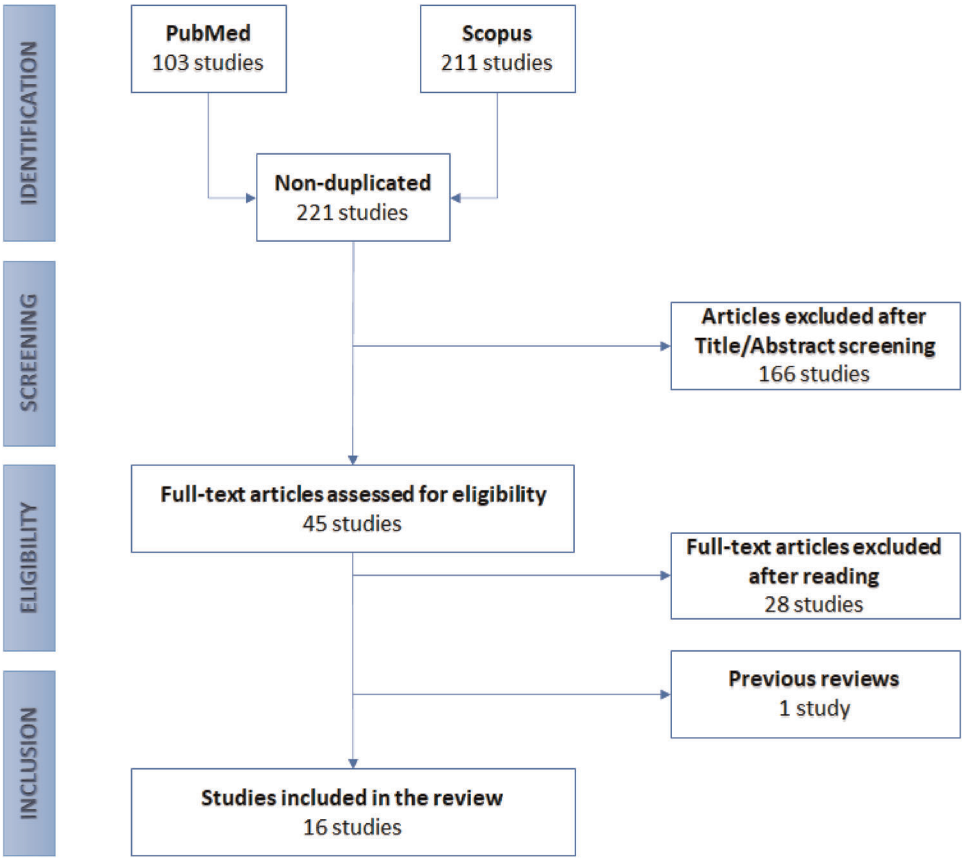

FIGURE 1
Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flow diagram.

The NLP part contained several terms, each belonging to a particular characteristic of the NLP methodologies. Of course, terms as *natural language*, *NLP*, *NLG* (an acronym for NL Generation), and *NLU* (standing for NL Understanding) were directly inherent to the scope. Terms like *computational linguistics* and *text mining* were included because directly related to the NLP field, and often utilized as interchangeable synonyms. For both of them, there are only slight differences. Sometimes, field practitioners disagree about those differentiations. Usually, computational linguistics concerns the development of computational models to study some linguistic phenomenon, also concerning other fields such as sociology, psychology, and neurology. For example, a successful CL approach may be designing a better linguistic theory of how two languages are historically related. NLP, instead, is mainly oriented towards solving engineering problems analyzing or generating natural language text. Here, the success of the NLP approach is quantified on how well the developed system resolves the specific task. Text mining, instead, usually refers to turning unstructured text into structured data to further exploit it, e.g. through statistical analysis (data mining). Some practitioners find NLP is a part of text mining. However, there is still not a consensus about it.

Instead, terms as *tokenization*, *word embedding*, *rule based*, *regex*, *regular expression*, *bert*, and *transformers* refer to the methods to pre-process, extract features and models used to elaborate unstructured text, while *automated reporting*, *summarization*, *named entity recognition*, and *topic model* refer to specific tasks that can be performed on the text and are typical in the medical domain. Furthermore, we included some other generic terms: *text analysis*, *free text*, *biomedical text*, *medical text*, *clinical text*, *biomedical notes*, *medical notes*, *clinical notes*; and *linguistics*.

The medical part, instead, contains all terms related to the LBP and spine disorders conditions: *low back pain*, *lumbar*, *intervertebral disc degeneration*, *intervertebral disc displacement*, *spondylarthritis*, *spondylolisthesis*, *disc herniation*, *spine surgery*, *spondylarthrosis*, and *durotomy*.

2.4. Inclusion and exclusion criteria

This systematic review aimed to gather all the studies concerning the utilization of NLP in the diagnosis, prevention, and treatment of LBP. Straightforwardly, all the selected articles had to meet all the following inclusion criteria:

- LBP must have been between the main topics of the articles;
- NLP techniques must have been used in the studies;
- Subjects of the studies: all the articles must have been based on studies of the human spine pathology;
- Language: all articles must have been written in English.

Conversely, we excluded articles that did not meet the inclusion criteria for one of the following reasons:

- Low Back Pain or spine diseases were not considered;
- No automatic tool of text analysis were exploited;
- Animal studies.

2.5. Quality of evidence

The methodological quality of included studies was assessed independently by two reviewers (L.A. and F.R.), and any disagreement was solved by the intervention of a third reviewer (G.V.). The risk of bias and applicability of included studies were evaluated by using customized assessment criteria based on the Quality Assessment of Diagnostic Accuracy Studies (QUADAS-2) [15]. This tool is based on 4 domains: patient selection, index test, reference standard, and flow and timing. Each domain is evaluated in terms of risk of bias, and the first 3 domains are also assessed in terms of concerns regarding applicability. Sixteen studies were rated on a 3-point scale, reflecting concerns about risk of bias and applicability as low, unclear or high, as shown in **Figure 2** (the details of the analysis are presented in Supplementary Tables S1 and S2).

3. Results

The searching queries were performed on November 6th, 2021, on two databases, namely PubMed and Scopus, resulting in 103 and 211 papers, respectively. Nonetheless, many of these articles were duplicates. So, as a first screening, we removed the repeated studies, resulting in 221 papers. Then, we analyzed the remaining articles' titles and abstracts. In this phase, we excluded the works not meeting the inclusion criteria. This operation reduced the number of eligible articles to 45. Among them, we encountered one narrative review [16], in which Groot et al. recently focused on the role the NLP in spine surgery in six studies from the recent literature. However, since these papers are extensively reported in this review, we did not further focus on their work here. So, the final screening was performed by reading the full text of each paper, leading to retaining 16 of them. **Figure 1** graphically shows the described selection process through a flow-chart diagram according to the PRISMA protocol.

In the following paragraphs, we analyze included studies particularly focusing on the tasks and models in which NLP is involved, also reporting the metrics used to evaluate the linguistic approaches.

3.1. Tasks

We identified three main NLP methodologies, namely classification, annotation, and prediction. Both first two approaches concern the identification of a category (class) to which a document belongs, differing for what the NLP methods are applied. In the classification approach, the system associates a label to each testing example (i.e., the patients' document). A classification system may provide information about a diagnosis, as a Computer-Aided Diagnosis (CAD) system, which the physicians may exploit to decide, for example, whether or not to operate on a patient. Also, healthcare providers may utilize such a system to improve quality control, while researchers may use it to retrieve a large cohort of patients suffering from a particular condition and then conduct some research analysis.

In the annotation approach, NLP is used to label the documents, too. However, it is implemented as a part of the entire system, thought to provide the classification outcome from another kind of data, such as radiological images. From this point of view, the NLP system is a way to automatize the annotation of a large amount of data by identifying specific phenotypes related to a disease condition. In this way, the second part of the entire system may be trained and evaluated on a significant larger amount of data than the cases where only human annotations are considered. This kind of approach is used to develop successful predictors of clinical outcomes from clinical data and better define indications for surgery. It may improve clinical outcomes, which also leads to avoid invasive spine care and reduce costs.

The third approach can be referenced as the identification of some category, too. However, here the scope is to predict some outcomes by exploiting previously acquired data (free-text notes, in this case). Healthcare providers may use such a system to predict some outcomes from the patients and thus arrange in advance the resources necessary for their care. Moreover, we further classified included studies based on the timeframe regarding surgical interventions. Thus, papers may also fall in the pre-, intra-, and post-operative task category, whether the task interests something before, during, or after surgery, respectively, as shown in Figure **Figure 3**.

3.1.1. Classification

3.1.1.1. Pre-operative tasks

We identified diverse studies in which the authors exploited pre-operative notes to identify useful diagnostic clues and findings. In detail, we retrieved:

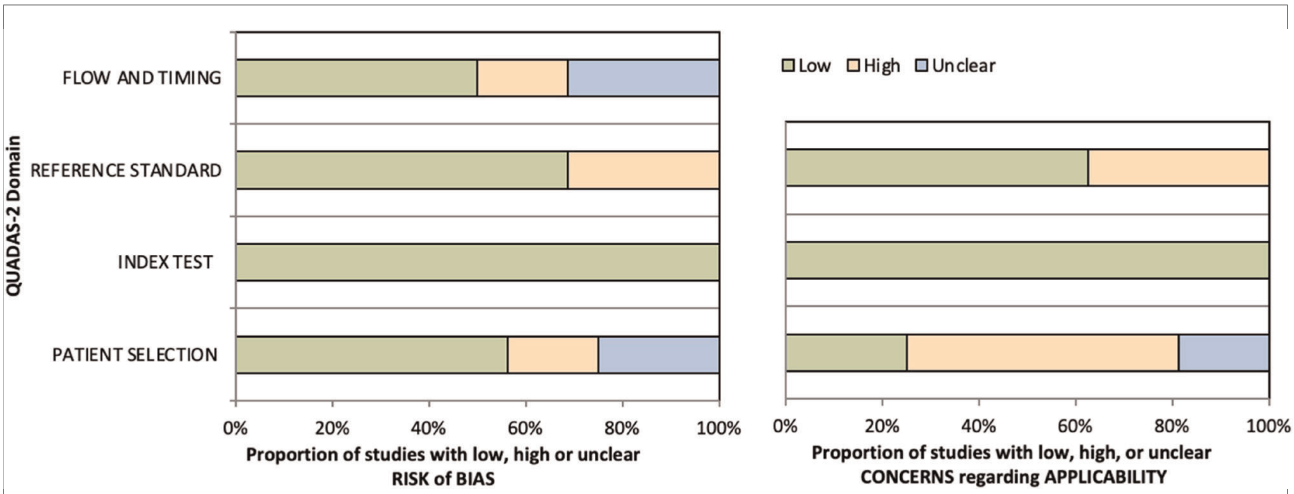

FIGURE 2
Summary of the methodological quality of included studies regarding the 4 domains assessing the risk of bias (left) and the 3 domains assessing applicability concerns (right) of the QUADAS-2 score. The portion of studies with a low risk of bias is highlighted in green, the portion with an unclear risk of bias is depicted in blue, and the portion with a high risk of bias is represented in orange.

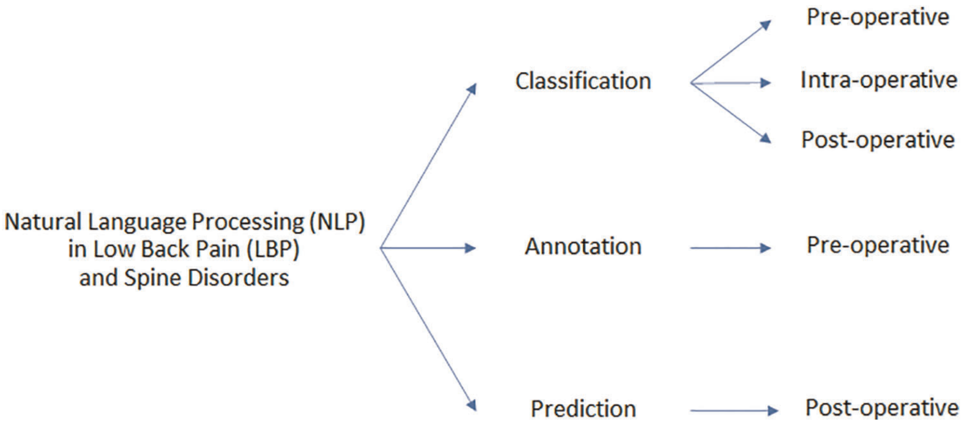

FIGURE 3
Schematic partitioning of the works concerning the application of NLP in LBP and related spinal disorders.

- 1 paper focusing on the identification of multiple imaging findings;
- 1 paper focusing on the diagnosis of acute LBP;
- 2 papers focusing on the identification of spinal stenosis;
- 3 papers focusing on the identification of axial spondyloarthritis (axSpA);
- 1 paper focusing on the identification of type 1 Modic endplate changes.

Following, we describe the tasks.

Imaging findings identification. To advance the care of patients suffering from LBP, discovering distinct subgroups with similar prognoses and intervention recommendations is a relevant task. Spine imaging findings alone are often insufficient to diagnose the underlying causes of LBP. In addition, they are often not of clinical significance since their frequent occurrence in asymptomatic individuals [17]. To understand the relationships between imaging findings and LBP, an important step is the accurate extraction of the findings, such as spinal stenosis and disc herniation, from large patient cohorts. NLP may help identify lumbar spine imaging findings related to LBP in large sample sizes. Tan et al. [18] worked on this task.

Acute LBP identification. LBP events can be classified either as acute or chronic. While the former is usually treated with anti-inflammatories, with the recommendation of returning to perform daily activities soon, care of the latter often involves physical therapy, spinal injections [19] and even spine surgery. Thus, different conditions lead to different treatment recommendations, leading to different costs to the healthcare systems. Miotto et al. [20] faced this task.

Identification of axSpA. AxSpA is a serious spinal inflammatory disease characterized by the additional involvement of peripheral joints, entheses, and other systems (including the eye, the gut etc.) [21]. As patients with axSpA often present with peculiar imaging features, developing a tool to facilitate the identification of this subset of patients is a key step to achieve in improving the care of this condition. To exploit large datasets, NLP may be used to identify concepts related to axSpA in text, and thus create a cohort of patients with (high probability of having) the disease. Zhao et al. [22] and Walsh et al. [23] dealt with this this task. The last team also exploited their previous work in their [24] to identify axSpA patients.

Stenosis identification. Spinal stenosis is a condition of narrowing of the spaces within the spine, which can compress the spinal canal (spinal canal stenosis, SCS) and the nerve roots exiting at each intervertebral level (neural foraminal stenosis, NFS). Such conditions often develop in the lumbar spine. Here, NLP was used to classify both SCS and NFS, also with a severity grading scale [25,26].

Type 1 Modic endplate changes identification. Modic changes consist of magnetic resonance imaging (MRI) signal alterations affecting the endplates of the lumbar spine and are particularly frequent in patients with LBP [27]. For this reason, Huhdanpaa et al. [28] employed NLP to identify the Type 1 Modic changes from radiology reports.

3.1.1.2. Intra-operative tasks

We identified diverse studies in which authors exploited operative notes to find evidence of some surgery complications. In detail, we retrieved two papers focusing on incidental durotomy (ID) identification and another one focusing on vascular injury (VI) identification. Such complications have potential implications for recovery, causing the length of stay and costs to increase. Thus, an automated system for surveillance of these events is relevant to healthcare providers.

Incidental durotomy (ID) identification. Incidental durotomy (ID) is a common intra-operative complication during spine surgery, occurring up to 14% of lumbar spine surgeries [29]. It is defined as an inadvertent tearing of the dura during surgery with cerebrospinal fluid (CSF) extravasation or bulging of the arachnoid [30]. The group of *Karhade and Ehresman* faced the problem of automatizing detection of ID events from operative notes [31,32].

Vascular injury (VI) identification. The terms vascular injury (VI) refers to the trauma of blood vessels (either an artery or a vein). It is a common event during spine surgery, often resulting in serious bleeding, thrombosis, and additional complications. Karhade et al. [33] dealt with the problem of detecting VI events from operative notes.

3.1.1.3. Post-operative tasks

Classification in post-operative tasks serves to identify events occurring after the surgical intervention, such as venous thromboembolism (VTE). VTE results from the formation of a blood clot which may obstruct the blood flow locally (thus causing edema and pain) or may travel to distant sites causing local blood flow arrest (such as in pulmonary embolism). Dantes et al. [34] attempted to identify from post-operative radiology reports the occurrence of VTE in patients who underwent various kinds of surgeries, including spine surgery.

3.1.2. Annotation

Among the included papers, two implemented NLP to annotate radiology images. Lewandrowski et al. [35] classified findings related to spinal stenosis (both SCS and NFS) from pre-operative reports, while Galbusera et al. [36] trained the NLP model to identify several spinal disorders. In both cases, the authors retrieved the annotations for radiology reports and then used them to label the related images. However, in the study by Galbusera et al., it was not possible to identify the timing with respect to surgery, since they included several types of disorders, as well as patients undergoing post-operative radiological examination and follow-up.

3.1.3. Prediction

Prediction tasks focus on predicting post-operative outcomes. In their first paper, Karhade et al. [37], they attempted to identify required re-operations due to wound infections arising after lumbar discectomy, while in a subsequent study [38] they identified unplanned re-admissions of patients who underwent posterior lumbar fusion. Both the tasks were intended to refer to a period within 90 days.

3.2. Data

Data used in the analyzed studies is the free text from clinical notes. However, the kind of notes exploited by the authors may vary in dependence on the task the authors aimed to cover. A large proportion of papers used radiology reports. This is obvious for studies aiming at identifying imaging findings [18] and diagnose a specific condition [22,23,25,26,28,34], or at annotating images [35,36].

Other examples include operative notes, obviously used for the intra-operative tasks [31–34], and post-operative ones too [37,38]. Furthermore, the article from Karhade et al. [38], compared different kinds of clinical notes, including discharge summaries [22], and physicians and nursing notes. With the exception of

[36], in which Galbusera et al. exploited notes in Italian, all other studies referred to notes written in English language.

3.3. Models

The studies analyzed in this review used various kinds of NLP models. Referring to **Figure 4**, we identified such models as belonging to one of the following categories:

- *Rule-based* approach: exploits both linguistic and custom heuristic rules/patterns to make decisions on the input data
- *Machine Learning-based* approach: exploits statistical information from text to train the model to predict the right outcomes

Of course, some pipelines may exploit both the presented approaches, falling into the so-called *hybrid* approach category. Furthermore, the machine learning (ML)-based approach may be further split into two subcategories, grouping studies that used ML models and others which implemented deep learning (DL) paradigms.

Also, models may be categorized as belonging to:

- *Supervised* approach, which exploits labelled data to train the model;
- *Unsupervised* approach, in which the algorithm is not provided with any labelled data.

By taking into consideration the above definitions, it is reasonable to consider the rule-base models as belonging to the unsupervised class of algorithms, while the ML-based models may fall in both categories. Nonetheless, the supervised approach is usually more performant because the model learns directly from input-output pairs, while the unsupervised ones leverage only the input data. However, the former approach may require a lot of labeled data, a process that can be extremely time-consuming, requiring several human resources (annotators), especially for large datasets. Furthermore, in the healthcare field, annotators should necessarily have a degree of expertise in the domain. This is the same reason why NLP was used to automatize the annotation process of images in some of the analyzed studies.

3.3.1. Rule-based models

Rule-based models are concerned about simple searches of keywords among the text of clinical notes, often by also developing regular expressions (regex). These rules may consist of both syntactic and semantic rules, also leveraging knowledge from both linguistics and the application domain (knowledge-driven approach). To identify (and then remove) negated occurrences, authors usually exploits algorithms such as NegEx [39]. This approach was implemented in [20] to identify acuity in LBP, and in [28] to identify Type 1 Modic changes, while in [18,25,26] to identify several findings related to LBP and stenosis from MRI and/or x-ray reports.

3.3.2. Machine learning-based models

ML models are algorithms that leverage their experience on previously seen data to automatically improve their performance on some task. Thus, they leverage a data-driven approach, by learning discriminative content from a statistical representation of the input data. The authors of the paper encountered focused particularly on two models from the machine learning literature: Logistic Regression (LR) and eXtreme Gradient Boosting (XGBoost). The former was implemented in [20] for the acuity identification task and in [22] to identify axSpA. In both cases, the model was implemented together with a Least Absolute Shrinkage and Selection Operator (LASSO) regularization. The latter was particularly employed by Karhade et al. in several tasks [31–33,37,38]. Another used algorithm was the Support Vector Machine (SVM), employed in [23] to identify clues of axSpA and in [24] both to directly identify axSpA and to extract a feature for a multimodal random forest. Furthermore, authors in [34] exploited *IDEAL-X*, a tool introduced in [40] which exploits the online ML paradigm, to identify VTE following orthopedic surgery.

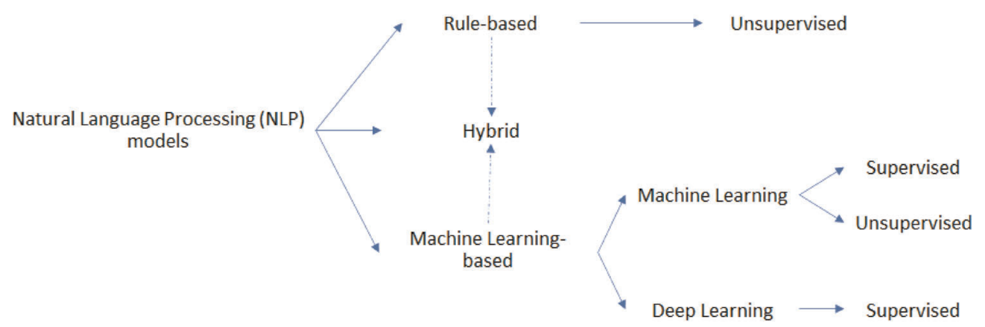

FIGURE 4
Schematic partitioning of the NLP models applied in LBP and related spine disorders.

3.3.2.1. Deep learning models.

The DL paradigm is a subfield of ML regarding the use of algorithms partly inspired by the brain structure and functioning, the so-called artificial (deep) neural networks. These algorithms are well known to perform better than ML in a large variety of applications. However, to be competitive they require a larger amount of training examples, and the training phase may be largely expensive in terms of time, especially when researchers do not have access to performant hardware facilities (i.e., Graphics Processing Units, aka GPUs). Probably for these reasons, only a few papers investigated the use of DL models. In [20], the authors compared a convolutional neural network (ConvNet) with classic ML and rule-based model. More recently, in [36] the authors fine-tuned a BERT [41] model pre-trained on general purpose italian text ("bert-base-italian-uncased"). Models like BERT are based on the Transformer's architecture [42], introduced a few years ago. Exploiting a pre-trained Transformer-based model to initialize the weights and then train on some downstream tasks has become a standard practice within the NLP community.

3.3.2.2. Unsupervised models.

All the above-reported studies leverage the supervised paradigm to train their models. The authors in [20] investigated the use of unsupervised models to identify acute LBP. They implemented a Latent Dirichlet Allocation (LDA) [43] to perform topic modeling, an unsupervised ML technique that captures patterns of word co-occurrences within documents to determine words' sets clusters (i.e., the topics). They identified a set of keywords among the topics and then manually reviewed them to retain only those that seemed more likely to characterize acute LBP episodes. In other words, they selected the topics including most of the keywords with high probabilities. Then, they considered the maximum likelihood among these topics as the probability that a report referred to acute LBP. Furthermore, the authors in [22] exploited the so-called multimodal automated phenotyping (MAP) [44], to identify axSpA from related concepts and coded features.

3.3.3. Hybrid models

For what concerns the hybrid paradigm, we encountered only one paper [18] exploiting it. Here, the authors implemented a logistic regression with elastic-net penalization leveraging several kinds of features. In particular, they also used features extracted with a combination of regex and NegEx.

3.4. Pre-processing

The pre-processing phase is dedicated to cleaning and elaborating input data. This step is necessary most of the time before feeding any algorithm in Computer Science and Artificial Intelligence approaches. Of course, NLP methods are not exempted.

Aside from tokenization (splitting the text into words, punctuation, etc.) and lower/upper-casing (normalizing words to their lower or upper-cased version), the most common procedures for text pre-processing are the following.

Stop words removal. Stop words are words highly common in a defined language, thus presenting the same likelihood to appear in both relevant and not relevant documents [45], i.e. carrying no informative content for the task in exam [28,31–33,37]. Also, some implemented the removal of generally less useful tokens, such as punctuation, numerals, and urls [20,37].

Stemming. Reduction of the words to their root form, usually by stripping each word of its derivational and inflectional suffixes [46]. Such a procedure aims to normalize the words from different inflections to a standard version [28,31–33,37].

Lemmatization. Similar to the stemming procedure, but instead of relying on heuristic chops of the words, leverage on vocabulary and morphological analysis of words to remove inflectional ending [20].

Filtering. This procedure discard words (or *n*-grams, i.e., a sequence of *n* words) occurring less than a fixed threshold in the entire (training) dataset. Because of their low prevalence, these words are not informative. This step reduces the number of misspelled words. The removal automatically reduces the dimensionality of word/document representations (i.e., the number of features), helping the model focus on the relevant features. Instead of discarding, the authors in [20] corrected to the terms in the vocabulary having the minimum edit distance (i.e., the minimum number of operations required to transform one string into the other).

3.5. Feature extraction

The term "feature extraction" refers to the procedure of combining variables from the data in order to provide a representation of each sample to be fed into (ML-based) models. The most common methods to extract features from text are:

Bag of Words (BoW). The Bag of Words model represents each document with a vector, in which every entry corresponds to the absence/presence (or the counting) of a specific word occurring inside that document [20,23,24,31,37]. The dimension of each vector is equal to the number of words encountered inside a corpus (e.g., a corpus built by the clinical notes collected). Given that, it is clear how the BoW representation is a sparse representation, i.e., every document shows a way greater number of absent words.

Bag of N-grams (BoN). The Bag of *N*-grams model is analogous to the BoW model. The only difference is that each feature is associated with an n-gram, i.e., a sequence of n words. Of course, several BoN models with different n may be combined together [20,23,24].

Engineered features. Features are extracted by leveraging the domain knowledge. For example, in [20] the authors retrieved a set of 5154 distinct n-grams based on concepts related to acute LBP episodes, while in [22] the number of occurrences of some concepts in free-text were used as features.

Word embeddings. Word embeddings are a way to encode the meaning of each word in a real-valued and non-spare vector representation. Models to retrieve this kind of representation, such as *word2vec* and *GloVe*, thus provide word representation such that the words with similar meaning or context are encoded in representations that are closer in the vector space. Thus, when a word has different meanings in the corpus, its representation is different depending on its context. This kind of feature extraction is exploited more whenever the final model consists of some neural networks, thus belonging to the DL-based approaches. In fact, we encountered word embedding features only in one paper [20] that explored the use of such an approach, using the *word2vec*'s *skip-gram* algorithm and a convolutional neural network. In [36] word embeddings are created internally by the BERT model and are initialized by the "bert-base-italian-uncased" pre-trained model.

3.6. Feature manipulation

With the term "feature manipulation" we indicate procedures adopted to regularize the features, thus improving their carried information (regularization strategy), or to reduce the feature space, in order to exploit in the next steps a reduced number of the most relevant features (feature selection). For the former case, the Term Frequency-Inverse Document Frequency (TF-IDF) strategy aims to assign to each term in a document D a weight that is directly proportional to the term frequency in D and is inversely proportional to the term frequency in all the documents of the corpus. In this way, it regularizes the features by balancing the rare ones with the most common ones. By the way, this method is applicable to both BoW and BoN models [20,31–33,37], and engineered features [20], too. For the latter case, it usually concerns discarding the features less representative in the (training) dataset. In the case of BoW and BoN features, this step is equal to performing a filtering step on the text during the pre-processing phase. However, in [23] the authors evaluated the discriminative power of each feature w in relation to each class c by the following equation

$$D_c(w) = \frac{1 - p(c)}{1 - p_w(c)} \tag{1}$$

in which $p(c)$ is the prevalence of class c among the training snippets and $p_w(c)$ is the prevalence of the class c among the training snippets containing the feature w. The features which occurred at least in two snippets and presents $D_c(w) \geq 2$ for every class c were retained.

3.7. Evaluation metrics

The metrics recognized in the analyzed papers can be divided into the following categories. The scope of this section is to help future research orientate them into a vast amount of metrics and choose the ones that better fit their research.

3.7.1. Discrimination metrics.

This kind of metrics measures the model's ability to map input data into separated classes. If the model employed is of the probabilistic kind (i.e., it outputs a probability instead of directly outputting the class), a threshold is applied to map the model's output to the class labels. Several metrics fall into this category, each having a specific meaning. Following, we reported the most common ones encountered in our study. Since most classification tasks were binary, we report the binary version of such metrics for simplicity and brevity purposes. However, in most analyzed papers, multi-class problems (classifying a sample to one label out of several classes) were approached as more binary tasks.

The entire set of the found discrimination metrics can be achieved from the confusion matrix (**Table 1**), a table layout that correlates the actual conditions of the samples, positive (P) and negative (N), with the conditions predicted by the model (PP and PN). It allows to easily visualize the number of correct predictions, both true positives (TP) and true negatives (TN), and the number of ill-classified samples, both false positives (FP) and false negatives (FN).

The first metrics we introduce are the True Positive and the True Negative Rates (TPR and TNR, respectively), as defined in Eq. 2. These measures quantify the ability of the model to classify the positive (and the negative) samples in the evaluation dataset. In the analyzed works, they are often indicated with other names. Usually, the name by which they are addressed depends on the field of application. In medicine works, it is not strange to find TPR and TNR reported as *sensitivity* and *specificity*, respectively, while, especially in AI-related papers, TPR is often presented as *Recall*.

$$\begin{aligned} TPR &= \frac{TP}{P} = \frac{TP}{TP + FN} \in [0;1] \\ TNR &= \frac{TN}{N} = \frac{TN}{TN + FP} \in [0;1] \end{aligned} \tag{2}$$

Other useful metrics are the Positive and Negative Predict Value (PPV and NPV, respectively), as defined in Eq. 3. They quantify the ability of the model to not misclassify the negative (and the positive) samples in the evaluation dataset. Thus, the PPV metric is often referred to as *Precision*.

$$PPV = \frac{TP}{PP} = \frac{TP}{TP + FP} \in [0;1]$$
$$NPV = \frac{TN}{PN} = \frac{TN}{TN + FN} \in [0;1] \quad (3)$$

A more general metric, quantifying the general ability of the model to correctly classify the samples, independently by their actual condition, is the *Accuracy*, defined as in Eq. 4.

$$Accuracy = \frac{TP + TN}{P + N} = \frac{TP + TN}{TP + FN + FP + TN} \in [0;1] \quad (4)$$

However, since this metric does not take into account a specific class, it is not very informative in case of a strong imbalance of the dataset. In fact, it is possible to show a high accuracy degree even when the model ill-classify all the samples belonging to the minority class. To clarify it, take into consideration the following example: we have 100 documents related to 100 patients; among these documents, only 3 samples belong to patients with an LBP diagnosis, while the others belong to the rest of healthy patients; if we classify each patient as healthy, we will still achieve an accuracy of 97%, which looks very good at a first impact, but it hides the fact that we are just predicting always the majority class. For this reason, it is good practice to prefer another metric but the accuracy, the F_1*-score*. The F_1-score, also addressed as F_1-measure, is the harmonic mean of precision and recall. It is defined as in Eq. 5, in which the score of the positive class is reported. The same score may also be computed for the negative class, by substituting Precision and Recall with their counterpart metrics, NPV and TNR.

$$F_1 = 2 \cdot \frac{TPR \cdot PPV}{TPR + PPV} \in [0;1] \quad (5)$$

Other widely used evaluation metrics are the Area Under the ROC and PCR Curves (AUROC and AUPCR, respectively), where ROC stands for Receiver Operating Characteristic and PCR stands for Precision-Recall Curve. Both curves are plotted considering the True Positive Rate against the False Positive Rate ($FPR = FP/P$), and the Positive Predict Value against the True Positive Rate, by considering the performances at different classification thresholds.

All of these metrics range between 0 and 1; the closer they are to the maximum value (i.e., 1), the more performant the system will be.

TABLE 1 Confusion matrix.

		Predicted condition	
		PP	**PN**
Actual condition	P	TP	FN
	N	FP	TN

3.7.2. Calibration metrics.

These kinds of metrics are a way to quantify the model's ability to get close to the population underlying probability. While discrimination measures the predictor's ability to separate patients with different responses, calibration captures the degree to which its numerical predictions match the outcomes [47,48]. In particular, some of the analyzed works reported intercept and slope measures [31–33,37,38] to assess the miscalibration of the system. Specifically, a positive/negative calibration intercept assesses the over-/under-estimation of the predictions, while a calibration slope evaluates the spread of the predictions; a slope greater/lower than 1 would indicate that the predictions are too moderate/extreme. For example, if $slope < 1$, the estimations are too high for patients who are at high risk and too low for patients who are at low risk [49]. However, calibration metrics are more relevant for clinical but computer science practitioners. Furthermore, the authors of the papers reporting calibration measures did not discuss their results in an exhaustive manner. Thus, in the analysis of these works (Section 4) we focused less on calibration metrics.

3.7.3. Overall performance metrics.

They are a way to measure the overall performance of the probabilistic predictions, being correlated to both discrimination and calibration at the same time. In most of the papers, the overall performances were assessed through the *Brier Score*. Designed to assess the quality of the probability predictions in forecasting tasks [50], the score introduced by Brier can be exploited in tasks in which a model assigns probabilities to a set of *mutually exclusive* and *discrete* classes. Such a score is defined as follows:

$$BS = \frac{1}{N}\sum_{i=1}^{N}\sum_{j=1}^{C}(p_{i,j} - y_{i,j})^2 \in [0;1] \quad (6)$$

In which we refer to N as the total number of samples for which the model is evaluated, to C as the total number of discrete classes, and $p_{i,j}$ and $y_{i,j}$ as the probabilistic outcome of the model and the actual class of the jth sample regarding the ith class, respectively. In particular, when the task is binary ($C = 2$), the Brier Score is equivalent to the *Mean Squared Error*:

$$BS_{C=2} = MSE = \frac{1}{N}\sum_{i=1}^{N}(p_i - y_i)^2 \in [0;1] \quad (7)$$

The Brier score may assume any value ranging between 0 and 1. However, being a measure of the prediction error, the closer it gets to the minimum value of the interval (i.e., 0), the more performant the model will be.

Another metric used to assess the overall performance is the *Standardized Net Benefit*. This decision curve analysis evaluates the clinical benefit of a predictive model over some default strategies across a range of threshold probabilities, defined as the minimum probability at which a patient/report is classified as presenting a particular condition [51]. In the analyzed papers reporting this decision curve analysis [31–33,37,38], classifying all the patients/reports as presenting the condition has been chosen as the default strategy. Also, comparisons with clinical gold standard codifications were present (see next paragraph).

3.7.4. Comparative strategies.

When evaluating a predictive model, it is often important to have a comparison with the performance of other models. In some cases, the comparison is made with some baseline methodology considered as the gold standard in actual clinical practice, like Current Procedural Terminology (CPT) and International Classification of Diseases (ICD). For example, in [31] the authors compare their model with both the kind of codes for durotomy (i.e., CPT=63,707, 63,709, 63,710; ICD-9=349.3; ICD-10=G96.11, G97.4). To address it, all the previously described metrics can be used to compare two or more models. Also, a particular version of the Brier Score is the so-called *null-model Brier Score*. It is a version of the Brier Score computed on a virtual (baseline) model generating a predicted probability equal to the population prevalence of the outcome ($=P/(P+N)$). Another strategy to compare the two models is by evaluating the p-values after performing some statistical test, like McNemar's one.

3.8. Explainability

AI is gaining momentum for a large number of different aspects of our society, including healthcare and will surely continue to have a significant influence in our daily lives the near future. However, current methods may achieve high performance of a specific task but often lack interpretability. The absence of more interpretable feedback together with the output from the model is a great inconvenience, especially in the clinical field. For what concerns the explainability, only *Karhade* and colleagues have addressed it, at both global and local (for the single subject) levels among included studies. It was possible thanks to the implementation of the XGBoost. Such an algorithm can provide the importance of each feature in a particular task. For example, in [31] the patient-level explanations were provided by highlighting the most important features (the words), used by the algorithm to detect ID, inside the text. Global explanations were provided averaging the importance score of each feature across all patients (the documents), to demonstrate the generally most important factors used for detection. Analogous reasoning was applied in their other works [37].

3.9. Softwares

We encountered several softwares and tools employed in the analyzed papers. The most used programming languages used to implement the NLP methods were *Java*, *Python*, and *R*. In particular, Java was used to implement rule-based models [18,28], also incorporating Apache Lucene (v 6.1.0) Application Program Interface (API), while Python and R [18,24–26] were usually exploited for ML approaches and conduct the statistical analyses.

Furthermore, various tools were used to perform manual annotations, such as REDCap [52] platform[1] [18,28] and Visual Tagging Tool[2] [23]. Also, in [36] the authors implemented a user interface with Python by exploiting the Python binding version of the graphical user interface toolkit Qt (PyQt[3]).

3.10. Domain-specific knowledge

Perhaps unusual in works of this kind, we conducted a typical NLP analysis of the papers included in this review to extract some domain-specific knowledge from the articles included in this review. In particular, we treated the collection of abstracts as a corpus from which we extracted domain-specific entities to build its glossary. We then retrieved the relations between them to create the knowledge graph of the domain we can call *Natural Language Processing in Low Back Pain and Spine Disorders*. To do so, we applied the $T2K^2$ suite of tools [53] to obtain the glossary in **Figure 5**, reporting the prototypical form of the entity (the term form most frequently attested in the corpus), its lemmatized form (Section (d)), and its frequency of occurrence. It is worth noting that these domain-specific entities may consist of single nominal terms but also of complex nominal structures. For ease of visualization, only the first part of the glossary (containing the most relevant terms) is reported in figure: the ranking

[1]https://www.project-redcap.org/

[2]https://lexsrv3.nlm.nih.gov/LexSysGroup/Projects/vtt/current/web/index.html

[3]https://riverbankcomputing.com/software/pyqt/intro

Prototypical Form	Lemma of Term	Frequency
NLP	NLP	46
patients	patient	37
NLP algorithm	NLP algorithm	18
natural language processing	natural language processing	13
lumbar spine	lumbar spine	14
lumbar	lumbar	21
algorithm	algorithm	21
specificity	specificity	20
incidental durotomy	incidental durotomy	12
Methods	method	18
sensitivity	sensitivity	16
axial SpA	axial spa	9
spine	spine	14
axSpA	axSpA	13
deep learning	deep learning	8
free-text operative notes	free-text operative note	6
anterior lumbar spine surgery	anterior lumbar spine surgery	5
models	model	11

FIGURE 5
Glossary extracted from the abstracts of the papers included in this work. Entities are ranked following their domain relevance. For ease of visualization, only the first part of the glossary (containing the most relevant terms) is reported.

follows the domain relevance of the entities, computed on the basis of their *C–NC* value [54]. By looking at the obtained glossary, it is easy to notice that the entities *NLP* (and its variations) and *lumbar spine* are the most relevant ones together with *patients*. We then selected these words as the most representative of the domain (we excluded the term *patients* because too generic) to compute their relations with the other entities in the glossary. In particular, the relations are computed on the basis of the co-occurrence of the entity in the core sentence (the one in which appear the entity under consideration) and the ones immediately before and after. The knowledge graph obtained with such entities and relations is reported in **Figure 6**. For ease of visualization, we filtered out terms with a frequency lower than 3 and the relations not occurring at least twice.

As interpretable from the figure, the *NLP* entity represents the core of the graph (and thus, in some sense, of the domain). It is worth noting the presence of the several diseases related to the *NLP* part (*incidental durotomies*, *axSpa*, *modic changes*, etc.), suggesting the obvious importance of these terms for the domain, and of the terms related to the computational part (*algorithm*, *models*, *artificial intelligence* etc.) and the data sources (*radiology reports*, *electronic health records*, etc.). However, both the *lumbar* and *spine* entities show a few prerogative relations, such as with *disc* and with *surgery*, respectively, that are not shared with the *NLP* core. Also, apart from the entity *natural language processing* that is just a variant of the *NLP* one, the only relation shared by all the three main entities is the one with *patients*. Besides being a very generic term, this result suggests the focus the authors put on the patients of their works, which also reflects the findings of the glossary.

4. Analysis

Our systematic review on the application of NLP to lumbar spine disorders eventually included 16 studies, whose main characteristics are summarized in **Table 2**. For the studies [18,20] using more than a model, we reported only the one with the best performance.

From a chronological point of view, Walsh et al. [23] were the first ones, in 2017, to apply NLP to LBP and related disorders. They first explored the axSpA language to manually select three terms that are predictive of such condition, namely "sacroiliitis", "spond(*)", and "HLA–B27 positivity," and their expanded term variations via regular expressions. Then, they extracted snippets of text from clinical notes and radiology reports, where a snippet is defined as a section of text containing a clinically meaningful concept surrounded by its context. Finally, they implemented a Support Vector Machine (SVM) algorithm for each concept to classify each snippet as intending the presence of axSpA or not. To do so, they extracted bigram features from the snippets and performed a discriminative power-based feature selection. They evaluated the system in a 10-fold cross-validation fashion, reporting metrics separately for each concept at the percentage of 95% (confidence interval) for accuracy (91.1%, 93.5%, 97.2%), PPV (91.1%, 93.5%, 97.2%), and NPV (91.1%, 93.5%, 97.2%). Also, they evaluated the system on an independent test set achieving comparable results. In total, the annotation for 900 "sacroiliitis"-related snippets, for 1500 "spond (*)"-related snippets, and for 1500 "HLA–B271"-related snippets were collected. The authors re-used the three developed models in [24]. In particular, the "spond(*)" related model was directly implemented in the classification of the axSpA identification task. Also, the output of the three models together was used in combination with other 46 coded features in a second experiment, what they called the Full algorithm. These other variables were extracted from structured data such as diagnosis codes for axSpA, laboratory data relevant to axSpA, medications, and comorbidities). In this second case, applied NLP models can be also viewed as feature extraction methods. They evaluated sensitivity, specificity, PPV, and NPV for both the Full algorithm (87.5%, 91.7%, 79.5%, and 95.2%, respectively) and Spond algorithm (95.0%, 78.0%, 61.3%, and 97.7%, respectively). Results were evaluated at 95% CI, determined through bootstrapping, with sampling with replacement of the observed data for 500 times. In total, 600 US veterans' electronic medical reports were used in their work, 451 for training and 159 for testing.

Zhao et al. [22] trained a Logistic Regression with LASSO with 100 random split iterations on 550 patients, in which 127 (23%) were manually determined to have axSpA meeting classification criteria and 423 did not. They exploited the Surrogate Assisted Feature Extraction (SAFE) method to extract a list of potential axSpa-related concepts from online resources such as MEDLINE. The SAFE method retrieved four disease concepts, ankylosing spondylitis (AS), sacroiliitis, HLA-B27, and spondylitis. For each patient, the numbers of positive mentions of each axSpA concept were combined with coded data: the number of occurrences of ICD code for AS and the healthcare utilization (i.e., the number of medical encounters in each patient's record). Then, the authors compared three models: Logistic Regression model; LASSO-LR, and the multimodal automated phenotyping (MAP) [44], an unsupervised approach that classifies phenotypes in EHR data. Although their behaviors were similar in terms of AUC (93.0%, 92.9%, 92.7%), sensitivity (70%, 71%, 78%), specificity (95%, 95%, 94%), and F_1-score (75%, 75%, 79%), the MAP algorithm was slightly better than the others. However, all three methods outperformed methods based on related ICD codes counting. To achieve these performances, they extracted 550 notes (among healthcare provider notes, discharge summaries, and radiology reports), randomly split 100 times into training and test sets.

In 2018, Huhdanpaa et al. [28] developed a pipeline of text pre-processing and concept identification at the document level, using a list of keywords and regular expressions to incorporate spelling variations and negations (NegEx algorithm [39]). They evaluated 458 radiology reports from the Lumbar Imaging with Reporting of Epidemiology (LIRE) study [55], with a prevalence of Type 1 Modic changes approximately of 10%, resulting in a sensitivity of 0.70, a specificity of 0.99, a precision of 0.90, an NPV of 0.96, and a F_1-score of 0.79. Results were reported for a 95% CI.

Tan et al. [18] used a similar approach to identify 26 imaging findings from radiology reports, producing dichotomous predictions for each report, where a positive assignment was made if there was at least one sentence with a keyword that was not modified by a negation term. Also, they applied a multimodal Logistic Regression with elastic-net to n-gram features and Regex and NegEx from the rule-based model (among others), resulting in a hybrid model. They fine-tuned the model hyperparameters on the development subsample with 10-fold cross-validation using a Receiver Operating Characteristic (ROC) loss function. Results, estimated at 95% confidence intervals using bootstrap percentiles on the test set based on 500 iterations, were reported for both the models, in terms of (averaged) sensitivity (0.83, 0.94), specificity (0.97, 0.95), and AUC

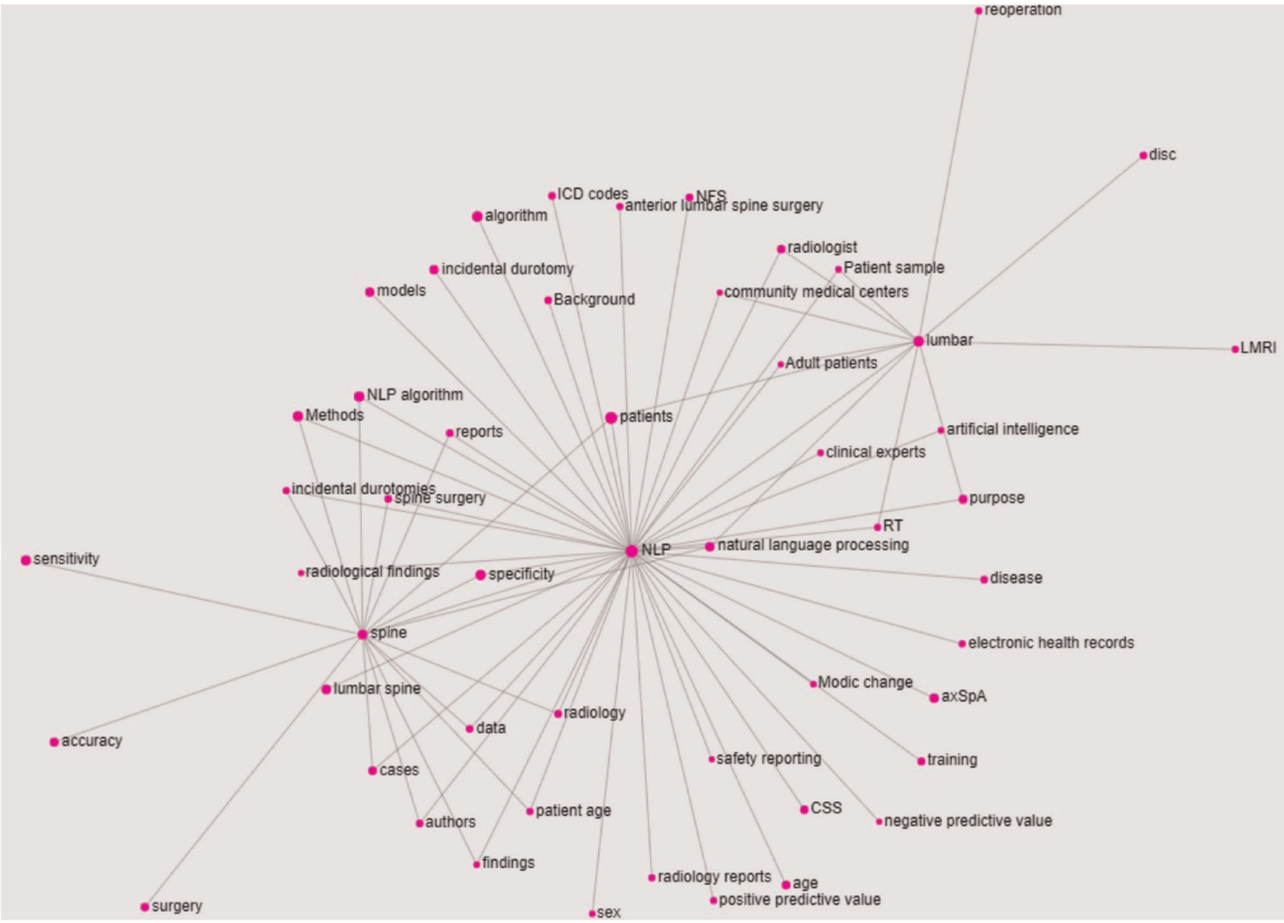

FIGURE 6
Knowledge graph built for the main entities of the domain extracted from the abstracts of the papers included in this work. For ease of visualization, only the terms with a frequency greater than 3 and the relations occurring at least twice are reported.

TABLE 2 Overview table of analyzed papers.

Study	Year	NLP task	Task category	Domain	Source	Model
Caton et al. [25]	2021a	Class.	pre-op.	SCS/NFS	Lumbar MRI reports	rule-based
Caton et al. [26]	2021b	Class.	pre-op.	SCS/NFS	Lumbar MRI reports	rule-based
Miotto et al. [20]	2020	Class.	pre-op.	acute LBP	Clinical notes	DL (ConvNet)
Walsh et al. [23]	2017	Class.	pre-op.	axSpA	Electronic medical records	ML (SVM)
Walsh et al. [24]	2020	Class.	pre-op.	axSpA	Clinical chart database	ML (SVM)
Zhao et al. [22]	2019	Class.	pre-op.	axSpA	Electronic medical records	ML (SAFE+MAP)
Huhdanpaa et al. [28]	2018	Class.	pre-op.	Type 1 Modic Endplate Changes	Lumbar MRI reports	rule-based
Tan et al. [18]	2018	Class.	pre-op.	LBP-related imaging findings	Lumbar MRI reports and X-ray reports	hybrid
Lewandrowski et al. [35]	2020	Annot.	pre-op.	SCS/NFS	Lumbar MRI reports	Not specified
Galbusera et al. [36]	2021	Annot.	/	spinal disorders	Lumbar X-ray reports	DL (BERT)
Ehresman et al. [32]	2020	Class.	intra-op.	Incidental durotomy	Electronic health records	ML (XGBoost)
Karhade et al. [31]	2020a	Class.	intra-op.	Incidental durotomy	Operative notes	ML (XGBoost)
Karhade et al. [33]	2021a	Class.	intra-op.	Vascular injury	Operative notes	ML (XGBoost)
Dantes et al. [34]	2018	Class.	post-op.	Venous Thromboembolism	Electronic medical records	ML (IDEAL-X)
Karhade et al. [37]	2020b	Pred.	post-op.	Reoperation due to infection	Operative notes	ML (XGBoost)
Karhade et al. [38]	2021b	Pred.	post-op.	Unplanned readmission	Operative notes	ML (XGBoost)

(0.90, 0.98). They also reported performances in detecting the 8 findings commonly found in subjects without LBP and the 6 findings that are likely clinically more important for LBP. In all the cases, the hybrid model outperformed the rule-based one, especially with regards to sensitivity and AUC metrics.

Building on the same principles, Caton et al. [25] implemented a rule-based model to assess the severity degree of SCS and left and right NFS (including bilateral cases). Each text block, parsed from the "Findings" section of radiology reports, individuates a discrete level from T12-L1 through L5-S1. The 6-point severity grading scale includes "Normal," "Mild," "Mild to Moderate," "Moderate," "Moderate to Severe," and "Severe." Assuming that normal anatomy can be presumed by the absence of specific comment by the radiologist, failure cases (no mentions to the conditions) were identified as the "Normal" class. To accomplish the task, the authors iteratively assembled a dictionary of non-standard terms (e.g., "marked" or "minimally") to facilitate the mapping of non-standard terms to the grading scale. They reported the accuracy of 94.8% of this system on an annotated random set of 100 LMRI reports, meaning in 93 misclassifications out of 1800 level instances. At the individual levels, NLP accuracy ranged from 86.0%at right L5-S1 to 100% in 5/18 level instances (27.8%). The authors used their system to analyze the effects of age and sex in SCS and NFS, and also to compute a composite severity score in [26].

For what concerns the identification of spinal stenosis, another study has employed the NLP method trained on 5000 manually labeled disc levels extracted from radiology reports [35]. Here, *Lewandrowski et al.* marked both the central canal and the neural foramina based on the radiologist's report. For the former, the following labels were used: "no signs of abnormality," "disc bulging without compromise of the thecal sac," "disc bulging compressing thecal sac (central canal stenosis)," and "disc herniation compressing thecal sac (central canal stenosis)." For the latter, instead, the reports were annotated as "no signs of abnormality," "left foraminal stenosis,tead, the reports were annotated "right foraminal stenosis," or "bilateral foraminal stenosis." The NLP tool was then applied on 17800 disc levels with radiology reports to generate labeled training data for the main deep learning method. The pipeline was similar to the DeepSPINE, proposed by Lu et al. a couple of years earlier [56]. However, no performance for the NLP model was reported in the paper.

For what regards annotation tasks, Galbusera et al. [36] fine-tuned the "bert-base-italian-uncased" pre-trained model to identify 12 spine disorders related findings from radiology reports written in Italian, such as the presence of spinal implants or loss of lordosis. For the training (fine-tuning) phase, they manually annotated 4288 reports, while to evaluate the resulting model they annotated 202 reports. For all findings, the model has generally shown high accuracies and specificities, the former ranging from 0.88 to 0.98 and the latter from 0.84 to 0.99. About the sensitivity metric, the model reported a lower performance, namely 0.5 for the "osteoporosis" and 0.63 for the "fractures" findings. The lower sensitivity can be attributed to the unbalanced nature of the dataset: such radiological findings were more frequently absent than present. About the F_1-score, it ranges from 0.63 (osteoporis, again) to 0.95. The author used the NLP model to train (and evaluate) the main DL algorithm, the ResNet-18 convolutional neural network [57], previously pre-trained on the ImageNet database.[4]

Returning to the classification tasks, Dantes et al. [34] used NLP to identify VTE in the post-operative period. They employed the IDEAL-X tool [40], using both the controlled vocabulary mode and the ML model. They found out that the former was able to reach a better performance in terms of sensitivity (97.2%) and specificity (99.3%), calibrated with 468 and evaluated on 2083 radiology reports. Conversely, with the second mode, they reached a sensitivity of 92% and specificity of 99%. Furthermore, the ML required around 50% of reports to be processed before achieving both metrics to be greater than 95%. For both models, results were reported withing the 95% CI.

Identifying surgical and post-surgical complications is indeed a hot topic in this field. *Karhade et al.* proposed a ML-based pipeline to identify ID [31] and VIs [33]. To extract features, they used the TF-IDF version of bag-of-words and an extreme gradient boosting model. They achieved a high performance for both discrimination and calibration metrics. Also, the Brier Score resulted in being lower than the null Brier Score in each case. Furthermore, in [31] and in [33] they compared their model with gold-standard methodologies exploiting CPT (Current Procedural Terminology) and ICD (International Classification of Disease) codes of the intra-operative events. Their model always outperformed these methodologies, also showing a higher standard net benefit at all thresholds. Ehresman et al. [32] used the same model to statistically analyze 1279 patients. Also, the same research unit exploited the same pipeline in the two prediction tasks, to anticipate reoperation due to wound infection after lumbar discectomy [37] and unplanned readmissions after lumbar fusion [38]. In the first case, the model was trained on 4483 patients and evaluated on 1377 patients, while in the second one totality of 708 patients were used, including 141 patients as the test set. In particular, in [37] their model achieved again better performance than CPT/ICD methodologies. Their studies

[4]http://www.image-net.org/

have shown the adaptability of their proposed pipeline to several tasks, to achieve both classification and prediction outcomes, but limited themselves to searching for more performant models.

From this point of view, the study from Miotto et al. [20] is interesting. They compared several kinds of models, belonging either to rule-based and ML-based (both ML and DL) methods, also including unsupervised models. They aimed to classify whether a patient suffered from acute LBP or not. They evaluated five pipelines. In the first one, a rule-based model was proposed, implemented as a keyword search supported by the NegEx algorithm. About other unsupervised models, they exploited a topic modeling framework, using the Latent Dirichlet Allocation (LDA) model, capturing patterns of word co-occurrences within documents; these word distributions define interpretable topics to which every document can be classified as. Topics referring to acute LBP were manually reviewed, then they considered the maximum likelihood among these topics as the probability that a report referred to acute LBP. About ML models, they implemented Logistic Regression with LASSO, employing BoN or engineered features. Finally, they implemented a convolutional neural network for the DL models category. They also compared the various methods with an ICD baseline, considering as acute LBP all the notes associated with the Low back pain ICD-10 code (M54.5). The rule-based method resulted as the worst model, with recall equal to only 0.03, even worst than the ICD-based one. However, it reached the greatest precision, equal to 0.71. Also, the topic modeling-based approach achieved comparable performance to ICD. The best performing model, however, was the network, achieving a precision of 0.65, recall of 0.73, F_1-score of 0.70, and AUROC and AUPRC equal to 0.98 and 0.72, respectively.

5. Discussion

An overview of the analyzed works is reported in **Table 2**. Interestingly, all the papers included in this review were published in the last few years, with the oldest one dated 2017. Among these, classification and pre-operative tasks were the dominant categories to have been investigated. Also, various domains have been investigated by the authors. Identifying axSpA and spinal stenosis (and related findings) were the most present tasks, and they were investigated in 3 studies each, respectively. For the latter, however, one of the studies focused on the NLP part for annotation. For what concerns intra- and post-operative tasks, *Karhade* (and *Ehresman*) [31–33,37,38] and their corresponding coauthors were particularly productive, constituting approximately one third of included studies on the topic. In addition, the review from Grotto et al. [16] also comes from the same research unit. In fact, they faced several problems, from both the classification and prediction categories. Nonetheless, they always employed the same pipeline to the various task. From a medical point of view, this confirms the adaptability to several domains of their approach, but from an NLP point of view, this sounds more like a limitation, having no improvements of the methodologies between consecutive works. In this regard, the study from Miotto et al. [20] looks more captivating, exploring and comparing different kinds of methods. However, *Karhade*'s team [31,33,37,38] was the only one investigating the interpretability of their system. This, of course, was an effect of choosing XGBoost as the classifier model (Section (h)).

Another thing is the distribution models' types. Five studies implemented rule-based models, while the rest of the papers used ML-based models. In particular, only two among them exploited DL architectures. As also shown by Miotto et al. [20], the performance of rule-based NLP can be limited. The main reasons are to be found among the complexity of the findings, their ambiguity in reports, and feature sets that are not sufficiently rich. Nonetheless, rule-based methods are intrinsically unsupervised, which means that do not require large annotated datasets, as ML-based ones (especially, when working with deep learning architectures), which is an obstacle to their implementation.

Most of the times, medical researchers used NLP to identify large cohorts of patients in order to conduct their research analyses. In other words, they developed systems to collect datasets by including patients with high probability (according to the developed NLP system) of presenting some condition, in order to conduct their analyses on a larger cohort than they would get with traditional data collection. From this point of view, classification and annotation approaches are even more similar. However, in the annotation tasks the NLP system is employed to develop another system able to identify some spine disorders from radiology images. However, the developed models in the analyzed works may be used by physicians and healthcare providers to improve patients' care. For example, identifying acute LBP before surgery may provide some insights to the physicians, whether to recommend a therapy against another. Similarly, predicting reoperation in the near future may help healthcare providers to allocate resources in a more efficient way. Analyzing patient outcomes and relative changes in costs applying these systems may be a future research trend. Also, most of the works leverage private databases, which is an issue for comparing various works. It is well known that clinical text is usually full of sensitive content, however, a future direction may be to publicly provide data with respect to the privacy policies. This would help the research community in comparing works with each other.

6. Conclusions

NLP is a promising technology that is being extensively investigated in the last year in multiple clinical fields, including spine disorders. Although preliminary, studies on the topic have demonstrated to effectively classifying different conditions and events, label documents and predict outcomes. However, additional studies on larger datasets are needed to better define the role of NLP in the care of patients with spinal disorders.

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.

Author contributions

Conceptualization, LB, FR and MM; methodology, LB, FR, LA, LV, GV, FDe and MM; writing - original draft preparation, LB, FR, LA and MM; investigation, LB; writing - review and editing, LB, FR, LA, FDA, LV, GV, RP, FDe, MM and VD; visualization, LB and FDA; supervision, FR, LV, GV, RP, FDe, MM and VD; funding acquisition, FR, GV, RP and VD. All authors have read and agreed to the published version of the manuscript.

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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.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsurg.2022.957085/full#supplementary-material.

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Posterior hemivertebra resection and reconstruction for the correction of old AO type B2.3 thoracic fracture kyphosis: A case report

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Background: Post-traumatic malunion is one of the main causes of kyphosis and usually has serious consequences. We report a case of kyphosis caused by an old AO type B2.3 thoracic fracture, which was corrected with posterior hemivertebra resection and reconstruction.
Case presentation: A 41-year-old male was diagnosed with kyphosis caused by an old AO type B2.3 thoracic fracture. Preoperative examination and preparation were performed. His exam images showed a comminuted fracture in the left half of the T12 vertebral body, while chance-type fractures were seen in the right half of T12 vertebral body and its accessories. During the operation, posterior hemivertebra resection and reconstruction techniques were used to remove nearly half of the left vertebral body of the affected vertebra, preserve the right vertebral body and the facet joints of the affected vertebra, correct the kyphosis, and rebuild spinal stability. The patient's low back pain was completely relieved, and his thoracic kyphosis was corrected at the seventh post-operative day. CT reconstruction of the spine showed that the residual vertebrae healed well during his nine- and 18-month follow-ups. Continuous callus formation was observed inside and outside of the titanium cage at the reconstructed site, and there was no sign of subsidence of the titanium cage. The heights between the vertebrae were restored to within normal ranges and the physiological curvature of the thoracolumbar spine was achieved. The patient recovered well.
Conclusion: This operation preserved the hemivertebral body and facet joints, and maintains intervertebral height and local stability, thus avoiding titanium cage collapse, titanium cage movement, and other complications. This surgical approach is ideal for treating complex thoracic vertebral kyphosis caused by old fractures, and is worth utilizing in the clinic.

KEYWORDS
hemivertebral, resection and reconstruction, thoracic fracture kyphosis, osteotomy, orthopedic

Abbreviations
LSC, Load sharing classification; FDI, flexion-distraction injuries; SPO, Smith-Petersen osteotomy; PSO, Pedicle subtraction osteotomy; BDBO, Bone-Dis-Bone osteotomy; VCR, Vertebral column resection; VCRs, multiple adjacent vertebrae and discs resection; UPVCR, Unilateral posterior vertebral column resection; PVCR, Posterior vertebral column resection.

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Introduction

Kyphosis is commonly seen in cases of congenital vertebral malformation, old spinal tuberculosis, old spinal trauma, ankylosing spondylitis, Scheuermann's disease, and other diseases. Post-traumatic malunion is the most common cause of kyphosis (1). Delayed or incorrect treatment of spinal fractures can lead to localized kyphosis. The AO type B and C fractures are types that require surgical treatment. Load sharing classification (LSC) is used to describe the severity of spinal fractures. LSC scores the degree of vertebral comminution, displacement of fracture fragments, and correction angle of the kyphosis. Fractures with an LSC >6 require anterior column reconstruction surgery to prevent kyphosis (2). Traumatic kyphosis can be classified as a mild deformity or rigid deformity based on local healing. Mild deformities are due to bony nonunion within the vertebral body or disruption of intervertebral tissue adjacent to the affected vertebra, which leads to persistent local fretting. Combined anterior and posterior approaches are usually required for anterior column reconstruction for this type of deformity (3, 4). Extents of surgical trauma are relatively lower when spinal shortening is not required, because surgeons can avoid the folds of the dural sac, reducing the incidence of neurological complications.

Rigid deformity is a kind of locally stable kyphosis caused by vertebrae becoming wedge-shaped during the fracture healing process. These cases can be corrected by a single posterior surgery. Whether anterior reconstruction is needed depends on the kyphosis angle and the selection of specific osteotomy techniques. Rigid deformity kyphosis correction requires shortening of the spinal column, which can lead to dural sac folds, increasing the risk of neurological complications.

In this paper, the authors introduce a new surgical technique—reducible deformity—for old thoracic AO type B2.3 fractures. To the authors' knowledge, this is the first report describing this technique for reducible deformities. This operation can be completed through a simple posterior approach, and hemivertebral resection and reconstruction technology can restore the height of the spinal anterior column, correct kyphosis, and achieve effective fusion of the anterior column, avoiding common complications such as subsidence of the interbody fusion apparatus.

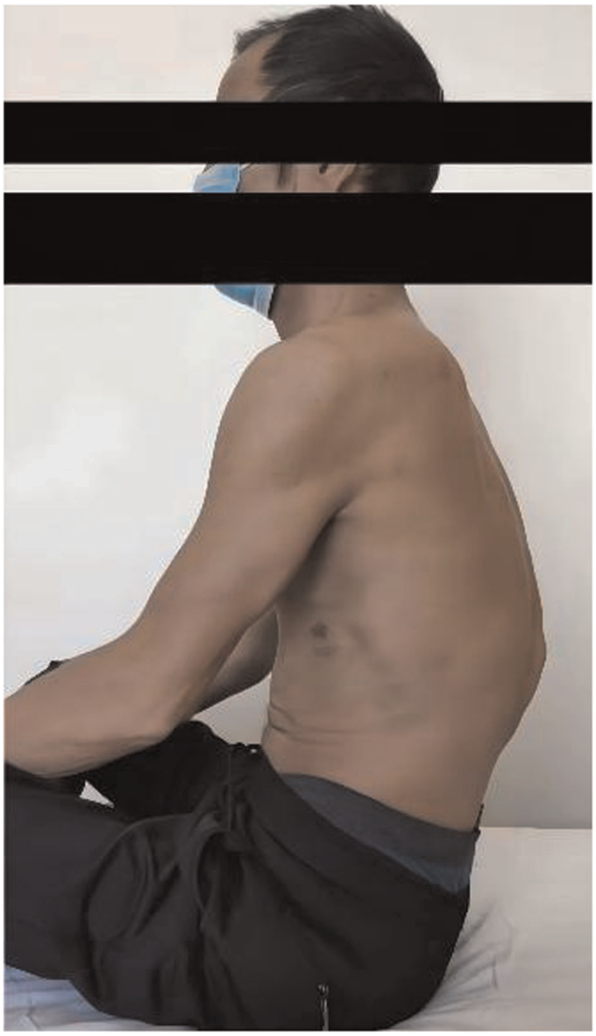

FIGURE 1
Pre-operative external observation.

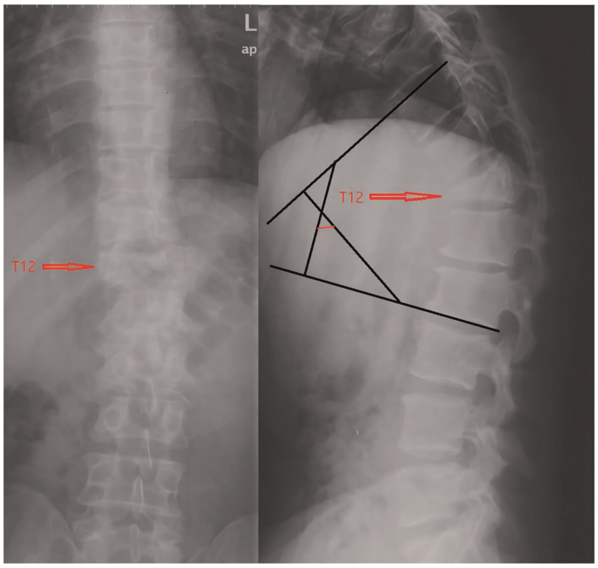

FIGURE 2
Anteroposterior and lateral radiographs of the thoracolumbar segment; Thoracolumbar cobb angle is 57°.

Case presentation

In June 2020, a 41-year-old man was admitted to the Second Affiliated Hospital of Harbin Medical University. More than two months prior, the patient had been injured by heavy objects. The patient developed chest and back pain and limited movement, accompanied by multiple injuries including in the right knee and right ankle. He received surgical treatment for knee and ankle joint fractures, and conservative treatment for thoracic vertebra and left clavicle fractures. Following the trauma, his chest and back pain were not completely relieved, and he gradually developed kyphosis (**Figure 1**). Neurological examination showed hypoesthesia of the skin on the lateral side of the right knee and right ankle and no other apparent neurological injuries. Anteroposterior and lateral radiographs of the thoracolumbar segment (**Figure 2**) showed that the T12 vertebrae had become wedge-shaped and the patient had developed severe kyphosis (thoracolumbar cobb angle is 57°). Three-dimensional CT (**Figure 3**) showed that the anterior edge of the T12 vertebral body was compressed to ¾ of the normal range, the anterior and left hemivertebra showed a severely comminuted fracture, the right hemivertebra was transversely split, and the bilateral pedicle and accessory structures had flexion-distraction injuries (FDI). Magnetic resonance imaging (**Figure 4**) showed fractures of T12, wedge-shaped vertebrae, and no apparent spinal cord compression. He was diagnosed with an old AO type B2.3 thoracic fracture based on imaging findings of posterior disruption of the osseous tissue, with vertebral body compression. He had an LSC score of 8 based on the following: 30%–60% comminution (2 points), fragments of at least 2 mm in size which were displaced >50% of the cross section of the structure (3 points), and kyphotic correction of ≥10° (3 points) (2). His chest and back VAS score was 6, and an ODI score could not be calculated accurately because the affected limb was accompanied by multiple unhealed fractures of the right lower limb. The patient had chest and back pain that did not respond to conservative treatment, unhealed local fractures and an unstable spine. Based on the above indicators, surgery was planned.

The patient was placed in a prone position after general anesthesia. A longitudinal incision was made with T10-L2 as the center, and a total of eight suitable pedicle screws were inserted into the bilateral pedicles of T10, T11, L1, and L2. Approximately 3 cm of the left rib connected to T12, the left transverse process of T12, the lamina, the facet joint, and the left half vertebra of T12 were removed with an ultrasonic bone knife. The left side of the T11/12 and T12/L1 intervertebral discs were removed *via* repeated curetting to expose the bony endplate. A bone chisel was inserted into the broken end of the right T12 vertebral body from the left side for local release. The right pedicle screw was implanted with a titanium rod under the radian convex side, and the local

FIGURE 4
Magnetic resonance imaging.

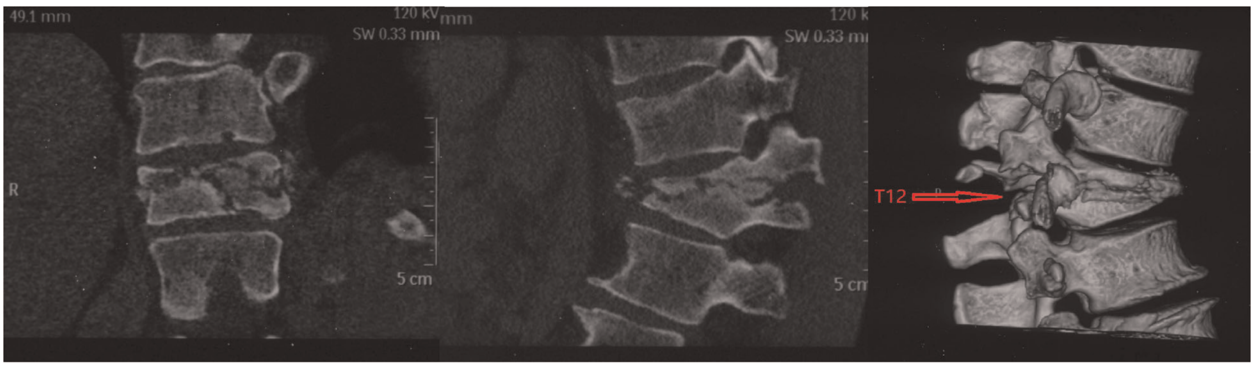

FIGURE 3
Three-dimensional CT.

kyphosis was corrected by the pull-reduction technique. Autologous granular bone was grafted between the intervertebral spaces of T11/12 and T12/L1 near the midline, and onto the fractured ends of the right vertebral body of T12. Autologous bone trimmings obtained from decompression was made into granular bone, and an appropriate titanium cage was filled and placed at the left edge of the T11-L1 gap. Titanium rods of suitable length were pre-bent to fit the physiological curvature of the spine and placed into the bilateral pedicle screw openings. Local moderate pressure was applied, and a crosslinking device was installed after locking with the top wire. C-arm fluoroscopy showed that the screws and titanium rods were well-positioned and that the length was suitable. The wound surface was repeatedly washed, two rubber tubes were placed beside the spinous process for drainage, and hemostasis was performed. Layered suturing was used to close the incision. Open reduction and internal fixation of the left clavicle fracture were performed in the supine position, and the patient was returned to the ward. Postoperative anti-infection, analgesic, and symptomatic treatments were performed as necessary, and one week after surgery, the patient was able to move out of their bed while supported.

One week after the operation, external observation images (**Figure 5**) were taken. Re-examination of thoracolumbar x-rays (**Figure 6**) and thoracolumbar 3D CT (**Figure 7**) showed that the physiological curvature of thoracolumbar was restored (thoracolumbar cobb angle is 11°), the fracture end of the right pedicle and posterior vertebral body of T12 was closed, and the left half of the vertebral body was well reconstructed. Nine months after surgery, the patient had no apparent thoracolumbar discomfort and had recovered well. A review of his thoracolumbar 3D CT (**Figure 8**) showed no significant changes in the physiological curvature of the thoracic vertebrae, good titanium cage positioning, continuous callus formation between adjacent vertebrae, and bony fusion of the fractured ends of the residual vertebrae. Eighteen months after the operation, 3D CT of the thoracolumbar segment was reviewed (**Figure 9**) and showed that the titanium cage was surrounded by the callus and had fused with the adjacent vertebrae.

FIGURE 5
Post-operative external observation.

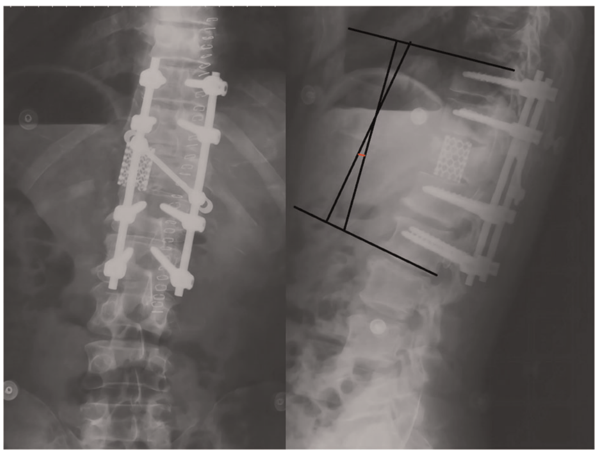

FIGURE 6
Anteroposterior and lateral radiographs of the thoracolumbar segment; Thoracolumbar cobb angle is 11° (One week after surgery).

Discussion and conclusions

In the AO classification system, FDIs are defined as b-type damage. FDI are usually caused by frontal shear of the frontal column or the frontal column rotation axis, and are characterized by posterior and middle column damage or tripillar damage (5). This type of injury has poor stability, and incorrect or delayed treatment may cause post-traumatic fracture nonunion and kyphosis, which is not uncommon in clinical practice. Many patients may develop back pain and neurological dysfunction, requiring surgical treatment (6). Our

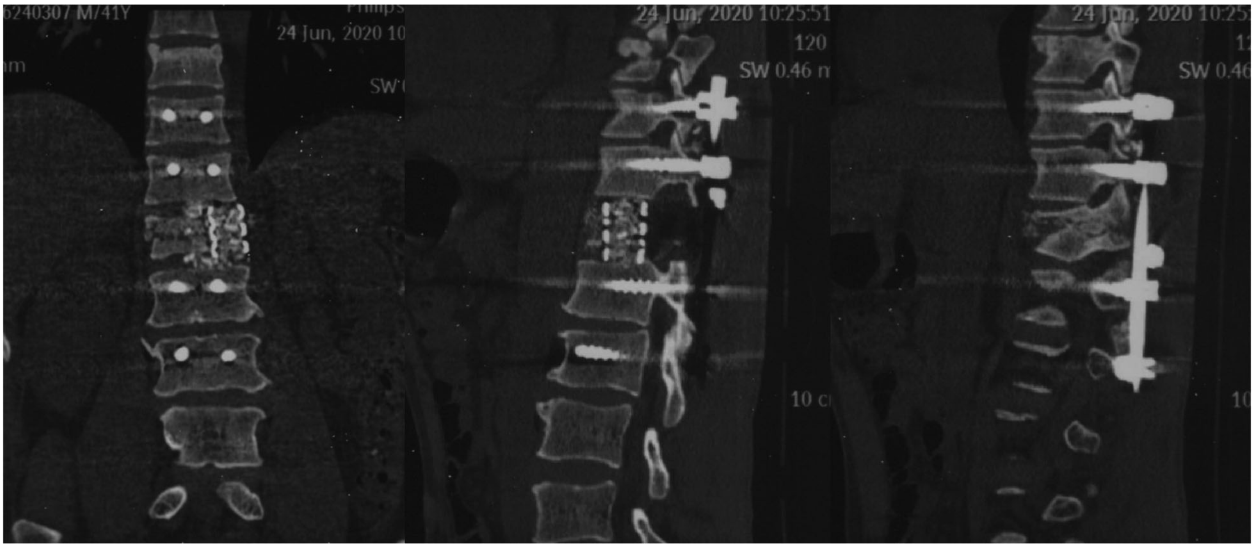

FIGURE 7
Sagittal and coronal CT of thoracic vertebra (One week after surgery).

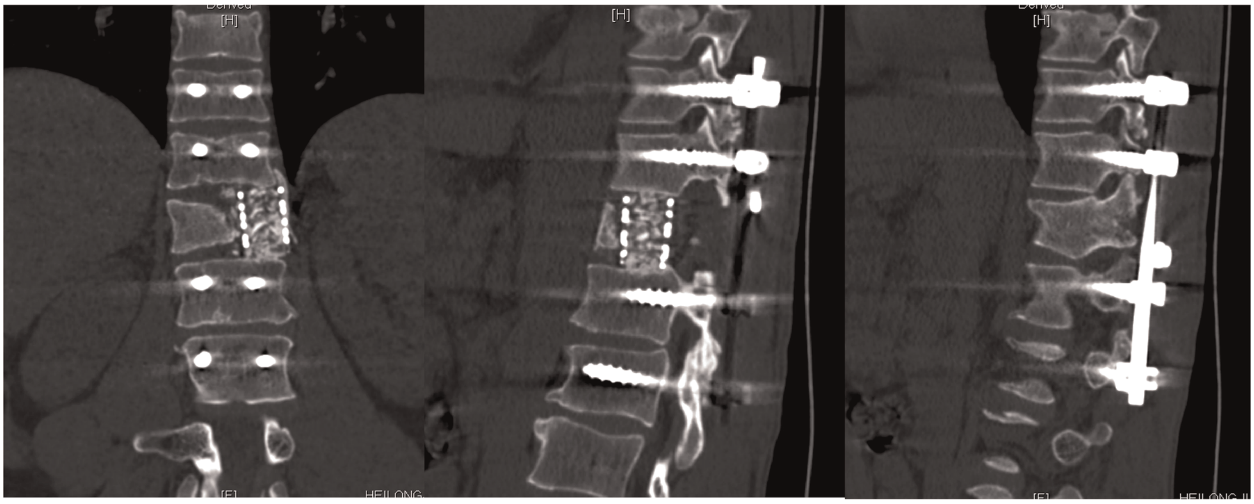

FIGURE 8
Sagittal and coronal CT of thoracic vertebra (Nine months after surgery).

procedural objective was to restore the normal physiological curvature of the spine and sagittal and coronal balance of the vertebral body, prevent further malformation development, and relieve symptoms of spinal nerve compression. Pakrer (7) believed that success of malformation correction procedures largely depends on the choice of surgical approach. The surgical approach can be a simple anterior approach, simple posterior approach, or a combined anterior and posterior approach. LSC has been effectively used in determining the choice of surgical approach. Patients with an LSC score <6 points should use a posterior approach, and patients with an LSC score >6 points should use an anterior approach. Adherence to these guidelines has improved the success of surgical reduction and fixation, decreasing rates of recurrence and/or fixation failure of kyphosis (7–9). However, the surgical risk and technical difficulty of the anterior approach are higher than those of the posterior approach, so the approach and surgical method to be adopted depends on the surgeon's proficiency in different surgical techniques and the specific injury context (5).

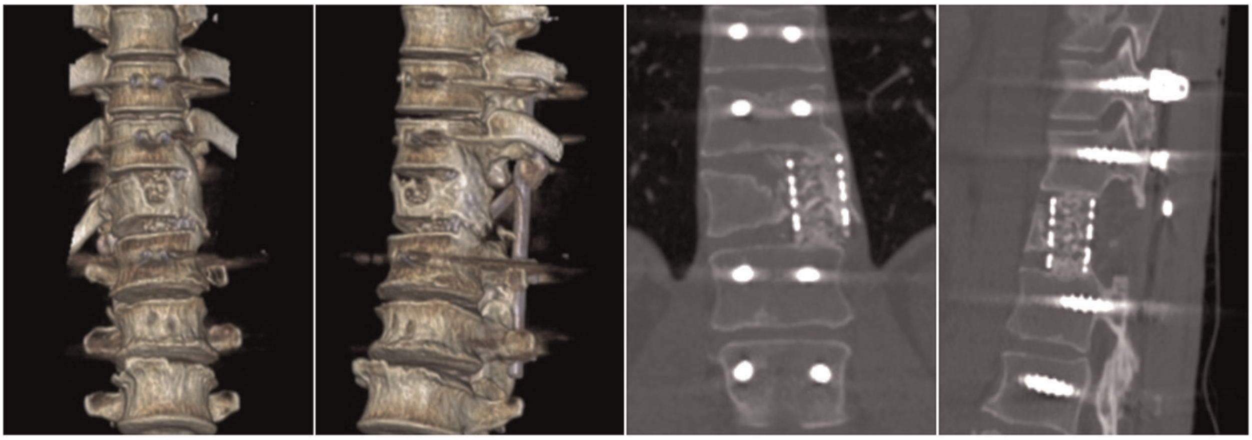

FIGURE 9
Thoracolumbar 3D CT (Eighteen months after surgery).

Osteotomy and orthopedic technology can be divided into six levels of difficulty and risk according to the volume of osteotomy needed and the kyphosis angle. The representative procedures for each of the six difficulty levels, in order of increasing difficulty, are the Smith-Petersen osteotomy (SPO), Ponte osteotomy, pedicle subtraction osteotomy (PSO), Bone-Dis-Bone osteotomy (BDBO), vertebral column resection (VCR) and multiple adjacent vertebrae and discs resection (VCRs) (10). Different osteotomy methods can be used for various diseases. For diseases with angular kyphosis, a higher-level procedure is generally required, which often require significant shortening of the posterior column at the surgical site and subsequent folding of the dural sac. These procedures are commonly associated with neurological complications such as spinal cord injury, spinal spondylolisthesis, and postoperative nail and rod breakage (11, 12). In recent years, Ding (13–15) and other scholars put forward unilateral posterior vertebral column resection (UPVCR) bone cutting technology; this technique excises the ipsilateral and most of the contralateral vertebrae obliquely through a unilateral approach, with approximately 330° decompression, and can be applied to angular kyphosis, Kummell's disease in elderly patients, and kyphosis correction treatment. Compared with posterior vertebral column resection (PVCR), UPVCR has advantages such as shortened operation times, reduced blood loss, and reduced incidence of nerve root injury, while achieving satisfactory correction of sagittal malformations, improvement of function, and pain relief.

In this case, the patient had an old AO type B2.3-old thoracic fracture, with a posterior osseous structure FDI combined with a type A vertebral fracture. The patient did not receive immediate treatment after his trauma, resulting in nonunion of the fracture and thoracolumbar kyphosis and bone absorption imaging of the left vertebral body. In this paper, the author applied hemivertebral resection and reconstruction techniques in the orthopedic treatment of kyphosis caused by an old AO type B2.3 thoracic fracture. The scope of resection of the vertebral body with this technique was smaller than that of UPVCR. Intraoperative resection of the type A damaged vertebral body was carried out through titanium cage reconstruction, and a bone pick was used to pry open the contralateral fracture end. The residual posterior fracture end was closed and reduced by pull-reduction and compression technology, while the anterior compression site was further opened. Autologous bone trimmings were grafted onto the intervertebral space and fracture space to achieve the best reduction and fusion. The author had the following recommendations regarding this technique: 1. The portion of the vertebral body that contained a type A injury was selected as the resection side; 2. The area of resection should not exceed the midline of the vertebral body; 3. The titanium cage was implanted at the edge of the vertebral body; and 4. The contralateral joint structure was fully retained. The above comments are based on the following theories: 1. In type B2.3 fracture combined with type A injury, most of the injured side is associated with a damaged cartilage endplate, making it unsuitable for structure retention due to poor local stability; 2. The titanium cage is placed at the edge of the vertebral body to retain as much original bone as possible, as this part of the bone has a strong compression resistance ability and can prevent subsidence of the titanium cage; 3. Retaining the contralateral facet structure can further increase intervertebral stability.

Hemivertebral resection and reconstruction is an orthopedic technique for kyphosis that can fully preserve intervertebral height and generate highly efficient fusion. It can be used in the orthopedic treatment of rigid kyphosis and Kummell's disease in elderly patients, as well as in anterior column reconstruction to alleviate kyphosis caused by a traumatic spinal fracture. This operation can be completed through the posterior approach and requires a smaller extent of surgical incision while offering strong local stability, less blood loss, and fewer neurological complications. Based on these advantages, this technique is worthy of further usage in the clinic for treatment of thoracolumbar spine fractures.

Data availability statement

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

Ethics statement

The Ethics Committee of Harbin Medical University ruled the study exempt from approval because this study was a case series. The patients/participants provided their written informed consent to participate in this study.

Authors' contributions

WZ and JXX contributed to the study design and performed the surgery. FCM contributed to writing and revising the manuscript. XZ and TTC contributed to collection of data. ZL and YSF contributed to revising the manuscript. 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.

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Epidemiological characteristics of traumatic spinal cord injuries in a multicenter retrospective study in northwest China, 2017–2020

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Background: Traumatic spinal cord injuries (TSCIs) are worldwide public health problems that are difficult to cure and impose a substantial economic burden on society. There has been a lack of extensive multicenter review of TSCI epidemiology in northwest China during the Corona Virus Disease 2019 (COVID-19) pandemic.

Method: A multicenter retrospective study of 14 selected hospitals in two provinces in northwest China was conducted on patients admitted for TSCI between 2017 and 2020. Variables assessed included patient demographics, etiology, segmental distribution, treatment, waiting time for treatment, and outcomes.

Results: The number of patients with TSCI showed an increasing trend from 2017 to 2019, while there were 12.8% fewer patients in 2020 than in 2019. The male-to-female ratio was 3.67:1, and the mean age was 48 ± 14.9 years. The primary cause of TSCI was high falls (38.8%), slip falls/low falls (27.7%), traffic accidents (23.9%), sports (2.6%), and other factors (7.0%). The segmental distribution showed a bimodal pattern, peak segments were C6 and L1 vertebra, L1 (14.7%), T12 (8.2%), and C6 (8.2%) were the most frequently injured segments. In terms of severity, incomplete injury (72.8%) occurred more often than complete injury (27.2%). The American Spinal Injury Association impairment scale of most patients did not convert before and after treatment in the operational group (71.6%) or the conservative group (80.6%). A total of 975 patients (37.2%) from urban and 1,646 patients (62.8%) from rural areas were included; almost all urban residents could rush to get treatment after being injured immediately (<1 h), whereas most rural patients get the treatment needed 4–7 h after injury. The rough annual incidence from 2017 to 2020 is 112.4, 143.4, 152.2, and 132.6 per million people, calculated by the coverage rate of the population of the sampling hospital.

Abbreviations
TSCI, traumatic spinal cord injuries; COVID-19, Corona Virus Disease 2019; ASIA impairment scale, American Spinal Injury Association impairment scale; ICD-10, International Classification of Diseases, Version 10; China CDC, China Center for Disease Control; HEMS, helicopter emergency medical service.

Conclusion: The incidence of TSCI in northwest China is high and on the rise. However, due to pandemic policy reasons, the incidence of urban residents decreased in 2020. The promotion of online work may be an effective primary prevention measure for traumatic diseases. Also, because of the further distance from the good conditional hospital, rural patients need to spend more time there, and the timely treatment of patients from remote areas should be paid attention to.

KEYWORDS

trauma, epidemiology, traumatic spinal cord injuries, COVID-19, northwest China

Introduction

Traumatic spinal cord injuries (TSCIs) can cause significant morbidity and mortality (1). These injuries are often caused by heavy injuries, traffic accidents, falling accidents, etc. and are centered in the labor age population and elderly population (2, 3). Despite the economic differences between countries or regions, this traumatic disease has caused a large loss of the working population, imposing a serious economic burden on patients and families, which leads to high health expenditure and economic losses (4, 5). Unfortunately, there is currently no effective treatment for patients with TSCI—severe damage to the spinal cord usually means permanent impairment (4, 6, 7). Therefore, attention should be paid to primary prevention. Understanding injury risk factors, incidence, and demographic characteristics can better guide the promotion of preventive measures and the allocation of medical resources (8, 9).

The global incidence of TSCI was 10.5 cases per 100,000 persons, but the incidence of TSCI varies across countries and regions (1). China is a country with rapid industrial development and frequent traffic flow; this brings more injury-causing factors, and the spinal trauma caused by it increases yearly (10). Therefore, it is necessary to update Chinese TSCI incidence data in real time. However, most existing studies have focused on East China, while there has been a lack of extensive multicenter review of TSCI epidemiology in northwest China in recent years (6, 11–14). The level of economic development in northwest China is far behind that in East and mid-China regions, and their characteristics of injury factors should be different, so its epidemiological data cannot fully refer to the data in the East and mid-China regions.

In this study, we aimed to discuss the epidemiological characteristics and risk factors of TSCI in northwest China. Thus, we used the multicenter retrospective data from 2017 to 2020 to expand the coverage area of previous studies and discuss the impact of Corona Virus Disease 2019 (COVID-19) on society (15).

Materials and methods

Location and participants

Northwest China comprises five provinces or autonomous regions: Shaanxi, Gansu, Ningxia, Qinghai, and Xinjiang, with a total population of 102.8 million. We chose Shaanxi and Qinghai, two provinces with representative development levels, as shown in **Figure 1A**. Shaanxi (SN) Province is a traditional industrial and agricultural region with a population of 38.8 million; Qinghai (QH) Province is an animal husbandry region rich in mineral resources, located in the northern part of the Qinghai–Tibet Plateau with a population of 6.1 million. In order to better distribute the research work, Shaanxi is further divided into northern (SN-N), central (SN-C), and southern parts (SN-S) according to climate and physiognomy. We dispatched investigators to the four regions separately and selected three to four hospitals with different administrative levels (provincial, municipal, and county) in each region, a total of 14 hospitals, as shown in **Figure 1B**. The patients' information was gathered from the medical records of these 14 hospitals between January 2017 and December 2020.

Study settings

Eligible patients were screened by the International Classification of Diseases, Version 10 (ICD-10) and its diagnostic code of TSCI. The final diagnosis was based on the patient's diagnosis at discharge/death. Four researchers retrospectively reviewed the medical records of 2,621 patients with TSCI admitted to the 14 hospitals in these two representative provinces between January 1, 2017, and December 31, 2020. The acquired information from patients' medical records included the patients' age, gender, occupation, marital status, time of injury, cause of injury, level of injury, severity of the injury, acceptance of surgical treatment, operative mode/approach, damaged segments, preoperative and postoperative scores, rehabilitation therapy, hospital duration, medical costs, and so on.

Executive organization and ethics statement

This project was jointly undertaken by the China Center for Disease Control (China CDC) and Honghui Hospital of Xi'an Jiaotong University. This study was approved by the ethics committee of Honghui Hospital of Xi'an Jiaotong University. The institutional review boards of the sampled hospitals

FIGURE 1
A total of 2621 patients form 14 hospitals in two provinces with TSCI were identified in this study (A) Sampling Provinces; (B) Sampling Regions for Multi-center Epidemiological Investigation.

approved the review process and waived the requirement to obtain patients' written informed consent.

Statistical analysis

All numerical data conforming to normal distribution were expressed as the mean ± standard deviation. The analysis of variance and χ^2 tests were used to analyze continuous and categorical data, Wilcoxon rank-sum tests were applied to examine the differences between the non-normally distributed continuous variables, and frequency analysis was used for examining data and calculating percentages. The experimental data were analyzed by SPSS 22.0 (SPSS Inc., Chicago). The figures were made by GraphPad Prism7 (GraphPad Software, CA, United States). $P < 0.05$ were considered as significant difference.

Results

General demographic characteristics of patients with TSCI from 2017 to 2020

A total of 2,621 patients with TSCI from 14 hospitals were identified in this study (**Figures 1B**, **2**). As shown in **Table 1**, out of these patients, 2,060 were male (78.6%) and 561 were female (21.4%), the male-to-female ratio is close to 3.67:1. The patients' ages ranged from 6 to 92 years, with an average age of

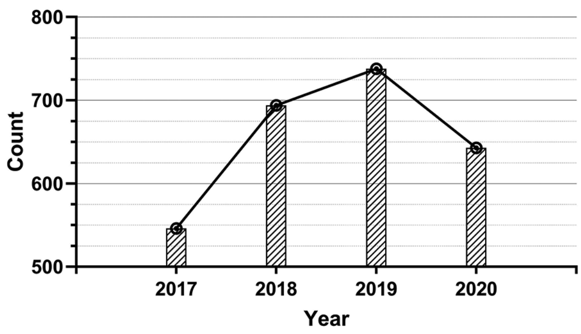

FIGURE 2
The annual count of TSCI patients during 2017–2020.

48 (±14.9) years and a median age of 49 (interquartile range 38) years. Among them, the average age of men and women is 48.0 ± 14.9 and 49.4 ± 14.9 respectively. According to the age distribution, it was found that young adults aged 21–40 years make up half of the TSCI population (49.9%). Regarding the occupation, farmers and herdsmen from rural or pastoral areas account for more than half of the total patients (58.1%), and the patients from urban areas are mainly workers (11.8%), students (5.5%), and retirees (5.6%). The other occupational groups included government officers (1.0%), technicians (1.1%), enterprise managers (1.1%), serviceman (0.2%), and others consisting of freelancers, unemployed individuals, and self-employed individuals who together accounted for 6.9% of the total patients. In addition, 8.7% of patients were unwilling to inform their occupational information for other reasons. Apparently, from 2017 to 2019, there were more patients each year than the previous year, while in 2020, there was a decrease of 12.9% compared with the number of patients in 2019 (Figure 2).

Etiology of the patients with TSCI

Analysis of the acquired etiological data showed that high falls were the leading cause of TSCI, indicating 38.8% of total patients ($P < 0.05$), followed by slip falls and low falls (27.7%), traffic accidents (23.9%), and sports (2.6%). Other factors include falling objects, violent fights, and other collisions, accounting for 7.0%. Table 2 shows the etiological composition ratio of TSCI in different age groups, in which there is no apparent difference in etiological composition ratio between ≤20, 21–40, and 40–61 years old groups ($P > 0.05$). However, the proportion of low-energy injury factors (i.e., slip fall or low fall) was higher in patients ≥61 years than in other age groups ($P < 0.01$); nearly half (45.9%) of patients with TSCI over 60 years old are injured by this factor. Table 3 describes the etiological composition of patients of genders. High fall (43.6%) is the most common cause of male patients with TSCI, while slip fall/low fall (37.6%) is the most common cause of female patients with TSCI.

Injury level

As can be seen from the statistics in Figure 3, TSCI occurred at the cervical, thoracic, lumbosacral levels, and the proportions in these levels were 33.0%, 36.8%, and 30.2%, respectively. We counted the number of cases per injury vertebral segment, and there were 79.0 patients with single-level spinal fractures and 20.1% patients with multilevel (≥2 levels) spinal fractures. Figure 3 shows that the distribution of segmental injury cases showed a “bimodal” pattern; analysis of these data indicates that the two peak injury levels of TSCI were C6 and L1 vertebra. Overall, L1, T12, and C6 were the most frequently injured segments, accounting for 14.7%, 12.2%, and 8.2% of the total cases, respectively. Further, the injury types of each vertebral segment are divided into fracture dislocation, distractive flexion fracture (chance fracture), burst fracture, and compression fracture. Roughly analyzing, the most fracture type of TSCI patients due to cervical injury is fracture dislocation, which accounts for 59.1% of cervical injuries. Compression fractures are more common in TSCI patients due to thoracic injury (exclude T12), which accounts for 48.3% of thoracic injuries; the major fracture type of TSCI patients due to lumbosacral injury (include T12) is burst fracture, which accounts for 55.9% of thoracic injuries.

Severity of TSCI

The severity of patients with TSCI was divided into complete quadriplegia (CQ), incomplete quadriplegia (IQ), complete paraplegia (CP), and incomplete paraplegia (IP) according to the degree of injury, as shown in Figure 4A. Most patients with TSCI present with IQ, accounting for 39.5%. The next is IP, accounting for 33.3%. Patients who suffered from complete injury included CQ and CP, accounting for 21.1% and 6.1%, respectively. Admission assessment results using the American Spinal Injury Association (ASIA) impairment scale system are shown in Figure 4B. From the pie chart of patients with TSCI patients, 26.8% of patients suffered from complete motor and sensory dysfunction (ASIA A), 11.2% suffered from complete motor dysfunction with some part of the sensory function retained (ASIA B), 24.2% had inefficient motor functions (myodynamia of most key muscles <3, ASIA C), and 37.7% had useful motor functions remain (myodynamia of key muscles >3, ASIA D).

The period between injury and admission

We recorded the patient’s waiting time from injury to admission. According to the data characteristics, we counted

TABLE 1 Demographic and etiologic characteristics of patients with TSCI from 2017 to 2020.

Characters	Years				
	2017	2018	2019	2020	Total
Total	546 (20.8%)	694 (26.5%)	738 (28.1%)	643 (24.5%)	2,621 (100%)
Age (years)					
≤20	18 (3.3%)	21 (3.0%)	34 (4.6%)	40 (6.2%)	113 (4.3%)
21–40	273 (50.0%)	322 (46.4%)	432 (58.5%)	282 (43.8%)	1,309 (49.9%)
41–60	105 (19.2%)	185 (26.7%)	140 (19.0%)	117 (18.3%)	547 (20.9%)
≥61	150 (27.5%)	166 (23.9%)	132 (17.9%)	204 (31.7%)	652 (24.9%)
Gender					
Male	460 (84.2%)	538 (77.5%)	585 (79.3%)	477 (74.2%)	2,060 (78.6%)
Female	86 (15.8%)	156 (22.5%)	153 (20.7%)	166 (25.8%)	561 (21.4%)
Occupation					
Government officer	17 (3.1%)	4 (0.6%)	0 (0.0%)	5 (0.8%)	26 (1.0%)
Technician	1 (0.2%)	9 (1.3%)	18 (2.4%)	0 (0.0%)	28 (1.1%)
Enterprise manager	3 (0.5%)	1 (0.1%)	9 (1.2%)	15 (2.3%)	28 (1.1%)
White-collar worker	22 (4.0%)	4 (0.6%)	1 (0.1%)	1 (0.2%)	28 (1.1%)
Blue-collar worker	51 (9.3%)	73 (10.5%)	98 (13.3%)	59 (9.2%)	281 (10.7%)
Farmer and nomad	310 (56.8%)	421 (60.7%)	413 (56.0%)	378 (58.8%)	1,522 (58.1%)
Student	42 (7.7%)	17 (2.4%)	30 (4.1%)	54 (8.4%)	143 (5.5%)
Serviceman	2 (0.4%)	0 (0.0%)	4 (0.5%)	0 (0.0%)	6 (0.2%)
Freelancer	0 (0.0%)	16 (2.3%)	11 (1.5%)	0 (0.0%)	27 (1.0%)
Self-employed	10 (1.8%)	3 (0.4%)	34 (4.6%)	46 (7.2%)	93 (3.5%)
Unemployed	0 (0.0%)	6 (0.9%)	21 (2.8%)	37 (5.8%)	64 (2.4%)
Retired	43 (7.9%)	32 (4.6%)	31 (4.2%)	40 (6.2%)	146 (5.6%)
Missing[a]	45 (8.2%)	108 (15.6%)	68 (9.2%)	8 (1.2%)	229 (8.7%)
Etiology					
Traffic accidents	120 (22.0%)	158 (22.8%)	237 (32.1%)	111 (17.3%)	626 (23.9%)
Sports and leisure	28 (5.1%)	7 (1.0%)	31 (4.2%)	3 (0.5%)	69 (2.6%)
Slip fall and low fall	159 (29.1%)	185 (26.7%)	161 (21.8%)	222 (34.5%)	727 (27.7%)
High fall	223 (40.8%)	289 (41.6%)	228 (30.9%)	276 (42.9%)	1,016 (38.8%)

(*continued*)

TABLE 1 Continued

Characters	Years				
	2017	2018	2019	2020	Total
Other factors	16 (2.9%)	55 (7.9%)	81 (11.0%)	31 (4.8%)	183 (7.0%)

TSCI, traumatic spinal cord Injury.
[a]Missing included patients who do not want to disclose information or whose information is not clearly documented.

TABLE 2 Etiological composition ratio of TSCI in different age groups.

Age group	Etiology					
	Traffic accidents	Sports	Slip fall/ low fall	High fall	Other factors	Total
≤20	30 (26.5%)	16 (14.2%)	33 (29.2%)	27 (23.9%)	7 (6.2%)	113 (100%)
21–40	326 (24.9%)	24 (1.8%)	239 (18.3%)	592 (45.2%)	128 (9.8%)	1,309 (100%)
41–60	138 (25.2%)	15 (2.7%)	156 (28.5%)	203 (37.1%)	35 (6.4%)	547 (100%)
≥61	132 (20.2%)	14 (2.1%)	299 (45.9%)	194 (29.8%)	13 (2.0%)	652 (100%)
Total	626 (23.9%)	69 (2.6%)	727 (27.7%)	1,016 (38.8%)	183 (7.0%)	2,621 (100%)

TSCI, traumatic spinal cord Injury.

TABLE 3 Etiological composition ratio of TSCI in males and females.

Gender	Etiology					
	Traffic accidents	Sports	Slip fall/ low fall	High fall	Other factors	Total
Male	439 (21.3%)	53 (2.6%)	516 (25.0%)	898 (43.6%)	154 (7.5%)	2,060 (100%)
Female	187 (33.3%)	16 (2.9%)	211 (37.6%)	118 (21.0%)	29 (5.2%)	561 (100%)
Total	626 (23.9%)	69 (2.6%)	727 (27.7%)	1,016 (38.8%)	183 (7.0%)	2,621 (100%)

TSCI, traumatic spinal cord Injury.

the 975 patients from urban and 1,646 patients from rural areas with TSCI separately in Figure 5. It was observed that most urban residents (88% of 1,646 patients) were able to rush to hospital for medical treatment within 1 h of injury. When most patients (55.4% of 1,646) with TSCI from rural areas arrived at regional hospitals which are qualified for treatment, 4–7 h had passed since the time of injury.

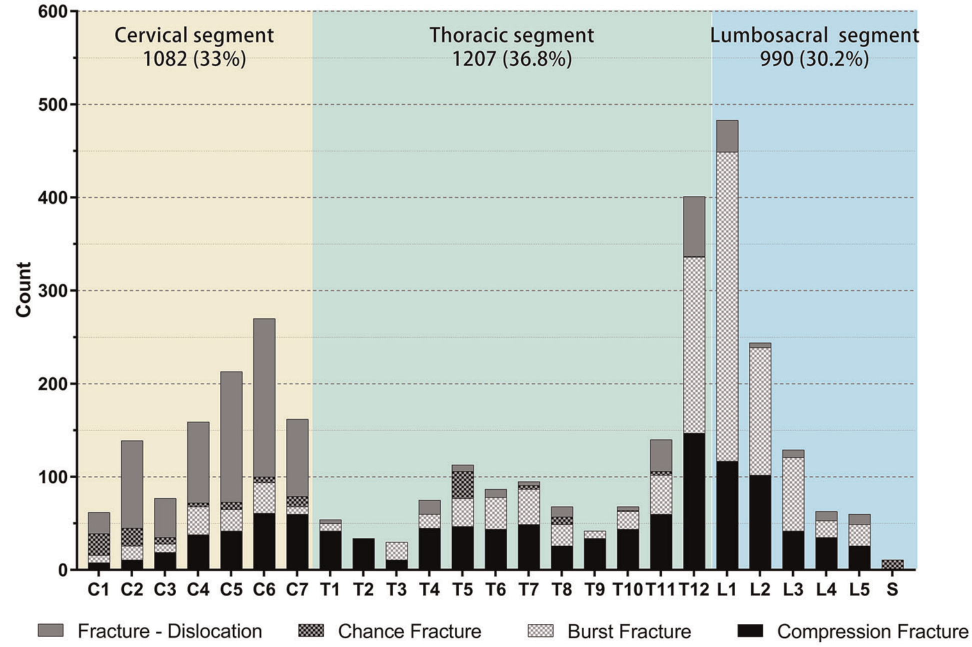

FIGURE 3
Distribution of fracture level for TSCI patients by the type of fracture (n = 2621).

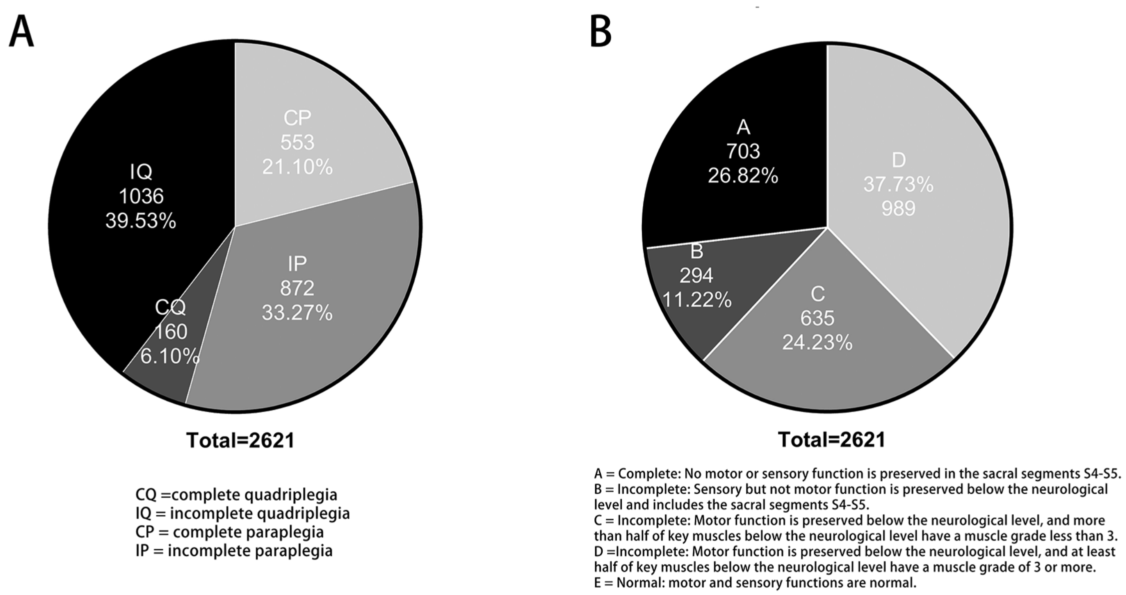

FIGURE 4
The severity of patients with TSCI: (A) The degree of injury; (B) Their spinal function after injury evaluated by ASIA impairment scale.

The annual count of TSCI patients form urban and rural

We divided the annual patient count into two groups: those from urban and those from rural areas. From 2017 to 2020, the annual number of urban patients was 185, 288, 323, and 172, which showed an increasing trend in the first three years, and decreased apparently in 2020 compared with 2019. From 2017 to 2020, the number of rural patients was 361, 406, 415, and 471, and the number of cases had been rising for four consecutive years.

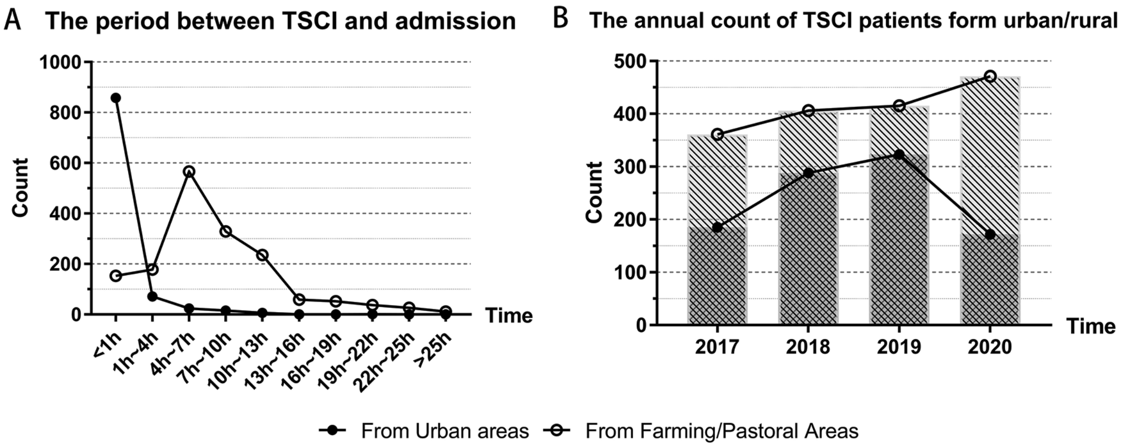

FIGURE 5
Urban and rural differences in patient treatment: (A) The patient's waiting time from injury to admission; (B) The annual count of TSCI patients form urban and rural.

TABLE 4 Treatment of TSCI and functional changes in discharge and admission.

Treatment of TSCI	Status on discharge					
	Cure[a]	Improvement[b]	Unchanged[c]	Deterioration[d]	Death	Total
Operative treatment	97 (4.8%)	448 (22.4%)	1,433 (71.6%)	11 (0.5%)	13 (0.6%)	2,002 (100.0%)
Conservative treatment	44 (7.1%)	72 (11.6%)	499 (80.6%)	0 (0.0%)	4 (0.6%)	619 (100.0%)
Total	141 (5.4%)	520 (19.8%)	1,932 (73.7%)	11 (0.4%)	17 (0.6%)	2,621 (100.0%)

[a]At discharge, the ASIA scale reached grade E.
[b]ASIA scale was improved than that on admission but still at an incomplete level (B/C/D).
[c]ASIA scales on admission and discharge were the same.
[d]ASIA scale was worse than that on admission.
TSCI, traumatic spinal cord Injury; ASIA, American Spinal Injury Association.

Treatment of TSCI and status on discharge

In terms of the treatment that TSCI patients received, 2,002 cases received operative treatment and 619 cases received conservative treatment. We regard the outcomes of the patients treated with operative or conservative treatment as a whole. We can figure out the change in patients' condition after receiving one of the treatments from the data in Table 4. Regardless of the treatment, about three-quarters of patients had no change in their ASIA impairment scales before and after treatment; among them, the patients who received surgical treatment accounted for 71.6% and the patients who received conservative treatment accounted for 80%. If the ASIA scale was improved on admission but still at an incomplete level (B/C/D), it would be regarded as improvement, with an improvement rate of 22.4% for those treated surgically 11.6% for those treated conservatively, about half of the former. Patients with the ASIA scale of Grade E at discharge were considered cured; the curing rate of both methods was unsatisfactory, being 4.8% for operative treatment and 7.1% for conservative treatment. In addition, there were a few cases of deterioration or death.

Estimation of TSCI incidence in northwest China

We can only infer the whole from the approximate relationship between the number of beds in our sampling hospital and the regional population covered by them. By referring to the China Statistical Yearbook (https://www.yearbookchina.com/) from 2017 to 2020, we combined the bed data of the five provinces in northwest China and concluded that the average annual bed number in northwest China during the 4 years was 6.194 beds per thousand people. The total number of beds in the 14 sampled hospitals was about 30,000, so it is estimated that the hospitals could cover a population of $30{,}000/6.194 \times 10^{-3} = 4{,}843{,}397$. The 4-year incidence rate of TSCI can be estimated as the ratio of TSCI patients admitted in the hospital to the total population covered by the hospital. These hospitals treated 2,621 patients with TSCI in the 4 years from 2017 to 2020. If we use these samples to estimate the population, the 4-year incidence rate of TSCI (per million people) was calculated to be 541.15 cases in the population covered by these hospitals. According to the survey data (**Figure 2**), the annual incidence rates from 2017 to 2020 were 112.4, 143.4, 152.2, and 132.6 per million people, respectively.

Discussion

Northwest China is an economically backward region in China with low coverage of health insurance and educational level, but it is still developing rapidly. Compared to eastern areas of China, such as Shanghai, Beijing, and Guangdong, northwest China has several unique characteristics. For example, the proportion of TSCI patients over 60 years in northwest China (24.9%) was higher than that in eastern regions. In addition, the proportion of farmers/nomads (58.1%) in the patients was apparently higher than that in the east (11, 16, 17). Many people are engaged in traditional manual labor or industrial production. Traffic factors and falls are both important injury factors for TSCI in the labor force (industry, agriculture, and husbandry). In the past, we have conducted single-center studies (15). However, despite its underdevelopment with low population density, the total area of five provinces in northwest China is nearly 3.08 million square kilometers, which is a vast area that covers about one-third of the land area of China. To get timely treatment, local patients usually choose a nearby medical center. Therefore, multicenter studies in multiple regions can better represent the whole region than single-center research. We collected the data of patients with TSCI admitted to 14 hospitals located in QH, SN-N, SN-C, and SN-S to understand the changes in the incidence of spinal cord injury patients before and after the emergence of COVID-19 (2017–2020). It can help optimize the allocation of medical resources and provide timely healthcare to the population of more areas.

Annual count results demonstrated an increasing trend in TSCI patients from 2017 to 2019. This trend is consistent with previous research findings (6, 15, 18). Unusually, the patient count in 2020 was apparently lower than that in the previous year; there were 12.8% fewer patients in 2020 than in 2019. We speculate that this is due to the shutdown and some "work-at-home" proposals implemented by the Chinese Government in the first two quarters of 2020 to prevent the COVID-19 epidemic. Recent studies on other traumatic diseases have reached similar conclusions (19–21). In addition, from the perspective of patients from urban or rural areas, the impact of these policies on the urban population is far greater than that on the rural population; the number of patients in the urban population in 2020 is only 53.3% of the last year, while the number of patients in rural areas in 2020 is still increasing compared with that in the previous year. We consider that this is related to the feasibility of shutdown policies and "work-at-home" proposals. In cities, where there are more office workers and students, it is easier to work or study online, which largely shields them from exposure to many outdoor injury factors, while agricultural or livestock production is hard to move online. Another indication is that the proportion of patients aged over 60 years in 2020 shows an increase. Due to degenerative bone changes and hypofunction of sensory and motor, nontraffic and low-energy injury factors are more likely to cause TSCI in elderly people than young and middle-aged people (22, 23). Combined with the epidemic policy mentioned earlier, this evidence is consistent with our conclusions. Although the COVID-19 pandemic brings immeasurable economic losses and damages to human health, it also facilitates the development of online work and learning, which makes it possible for many jobs to be performed online from home for a long time. In our conclusion, promoting online office work and learning will make a lot of sense to reduce the incidence of traumatic diseases among people at labor age, especially for urban residents.

In our investigation, the male-to-female ratio in patients with TSCI was 3.67:1, which is similar to the rate reported in other regions (6, 14, 24). This indicates that most of the patients with TSCI are male. This can be attributed to the fact that most workers in dangerous, physically demanding jobs are male and a greater proportion of drivers are male.

Most of the injuries were in the 21–40 age group (49.9%, 1,309 cases), followed by the ≥61 age group (24.9%, 652 cases) and 41–60 age group (20.9%, 547 cases). There are two age groups with high incidence. Such a "bimodal" trend seems to be different from the conclusions of previous studies. Most of the previous literature works described a "unimodal" trend with the highest age group around 40 ± 10 years old (6, 17, 25). This may be due to the difference in group spacing and the increased incidence of the elderly under the 2020 epidemic policy. The mean age of patients in our data was 48 (±14.9) years, which was higher than the domestic average age and global average age suggested by previous literature works (10, 26). We estimate that this result may be influenced by the aging of society and the policy of delaying retirement time.

Our study also revealed the etiology of the patients with TSCI in northwest China, including, traffic (23.9%), sports (2.6%), low falls (27.7%), high falls (38.8%), and other factors (7.0%). Groups were observed according to age first; we found that high-energy injury factors, such as high falls, were the most common cause of TSCI in 21–40 and 41–60 age groups, accounting for 45.2% and 37.1%, respectively, and in people over 60 years, low-energy factors, such as low falls or slips, accounted for 45.9% of the total cases. This is consistent with the conclusion of the study in Guangdong Province (6). Then, groups were observed according to gender, and the result indicated that males were more likely to have been impacted by high-energy factors causing TSCI.

Integrating the above etiological results, the age of high incidence of TSCI is still dominated by the labor age, especially in males. So, the labor security agencies of governments and the employers of workers should also strengthen labor safety measures and enhance safety education for employees (13). In addition, specialization and mechanization of agricultural and animal husbandry workers should be promoted so that dangerous and strenuous manual labor can be as far as possible from machines.

Spinal cord injury is usually associated with spinal trauma injury, and the levels of injury are corresponding. We counted the segments of the patient's vertebra and the types of fractures; it is the same as the previous literature; the proportions of injuries in cervical, thoracic, and lumbar vertebrae were similar, and the high incidence of spinal fractures caused by TSCI in each part was C5–C6, T11–T12, and L1–L2. The distribution of injury segments showed a "bimodal" distribution with C6 and L1 as the centers, with 1–2 adjacent segments (25, 27). Overall, the T11–L3 segment had the highest proportion of injuries, totaling 1,397 cases, accounting for 42.6% of all injured patients. The main fractural types of cervical, thoracic, and lumbar vertebrae are also different, which is related to their anatomical structures and mechanical characteristics.

From the severity of the injury and the outcome of treatment, our results revealed a less optimistic condition after treatment. As a result of consensus, incomplete injury (72.8%) occurred more often than complete injury (27.2%). Given the large number of patients with incomplete TSCI, this issue should be the focus of basic research related to neural regeneration, such as "how to promote the compensation of surviving neurons in the injured area" or "how to achieve differentiation of uninjured stem cells into neurons in the incomplete injured segment" (28). The ASIA impairment scale of most patients did not change before and after treatment in both the operational group (71.6%) and the conservative group (80.6%). This illustrates the importance of prevention in improving tertiary prevention measures and rehabilitation techniques as an essential guarantee of improved treatment outcomes. Moreover, the patients who were treated operationally had a higher improvement rate (22.4%) and deterioration rate (0.5%) than the patients who were treated conservatively (improvement rate was 11.6%, deterioration rate was 0.0%). Therefore, improving surgical methods to reduce postoperative complications is also a strategy to improve the efficacy of TSCI.

Our study also focused on urban–rural differences that had not previously been noticed by investigators. The annual difference in the number of cases was mentioned earlier, and we also compared the length of time between the onset and the treatment of patients in urban and rural areas. From our results, we can see that almost all urban residents can rush to the hospital for emergency treatment after getting injured immediately (<1 h), whereas by the time most patients from rural areas arrive at the hospital for treatment, it has been 4–7 h since they were injured. This reflects the delay in treating patients caused by poor transport conditions in rural areas. In fact, some hospitals in developed areas are already using helicopter emergency medical services (HEMS) to save treatment time for patients in remote areas (29). This kind of traffic measure is not restricted by the topography and is of great value for patients with various acute diseases in rural areas such as the Loess Plateau and the Qinghai–Tibet Plateau in northwest China. The problem is the high cost of HEMS, which also requires better allocation of resources and funding by the public health system.

Finally, we estimated the incidence of TSCI in northwest China based on the hospital coverage population from 2017 to 2020; the incidence rate ranged from 112.2 to 152.4 cases per million people, which is more than 23.7 per million people in Tianjin and 60.6 per million people in Beijing (16, 30). The incidence of TSCI is difficult to calculate due to the unpredictability of the occurrence of trauma. Sampling methods, inclusion criteria, regional demographic differences, and other factors will affect the results. Our estimated results only provide a reference for the incidence of TSCI in northwest China, and more scientific design and observational studies are needed to obtain its incidence accurately.

However, as a retrospective study, there are irreparable misrecords or incomplete information in the data we obtained, which may lead to a deviation between our results and the actual situation. Furthermore, we ignore the data on treatment cost and Medicare coverage, which can well reflect the economic pressure of patients and the development level of the region. Therefore, there is insufficient evidence in some descriptions of the severity of TSCI in northwest China.

Conclusions

In general, the incidence of TSCI in northwest China is high and on the rise. Due to the implementation of COVID-19 prevention and control measures, the incidence of TSCI among urban residents has decreased to a certain extent. Therefore, we suggest that promoting online office and learning is the effective primary prevention measure for traumatic diseases. In addition, due to the differences between urban and rural areas, rural patients need to spend more time getting to a good conditional hospital for treatment, and the problem of emergency transfer service still needs to be addressed.

Data availability statement

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

Ethics statement

Written informed consent was not obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

XW, JD, and CJ contributed to the study design. All authors contributed to the information collection. XW, JD, and CJ contributed to data processing and analysis. DH provided financial support and overall guidance. 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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A retrospective study of the mid-term efficacy of full-endoscopic annulus fibrosus suture following lumbar discectomy

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Aims: Full-endoscopic discectomy is associated with a high risk of disc reherniation due to the poor mechanical strength of the annulus fibrosus after scar healing. It is technically difficult to place a full-endoscopic annulus fibrosus suture. We designed an annulus fibrosus suture device that can be used to suture annulus defects under microendoscopy. The present study investigated the safety and feasibility of this technology.

Patients and Methods: We retrospectively analyzed the outcomes of patients who underwent surgical treatment for lumbar disc herniation (LDH) from January 2018 to October 2020. We compared 40 patients with LDH treated with full-endoscopic annulus fibrosus suture following lumbar discectomy (LD + AFS group) with 42 patients treated with lumbar discectomy alone (LD group) regarding demographic data, symptoms, and recurrence and reoperation rates. Lumbar MRI and CT were performed 3 and 12 months. A 10-point visual analog scale (VAS) and the Oswestry Disability Index (ODI) was used to evaluate pain and the lumbar spine function.

Results: The cohort comprised 82 patients, including 40 patients in the LD + AFS group and 42 in the LD group. All operations were successfully completed without serious complications. Reherniation occurred in no patients in the LD + AFS group and three patients in the LD group. The VAS scores for lumbar and leg pain and ODI score were significantly improved postoperatively ($p < 0.05$).

Conclusion: Compared with conventional lumbar discectomy, full-endoscopic annulus fibrosus suture following full-endoscopic lumbar discectomy is a safe and effective minimally invasive technique that reduces the LDH recurrence rate.

KEYWORDS

full-endoscopic discectomy, annulus fibrosus suture, lumbar discectomy, lumbar disc herniation, minimally invasive spinal surgery

Introduction

The intervertebral disc(IVD) is an important component of spinal stability and consists of an annulus fibrosus surrounding the nucleus pulposus and the upper and lower cartilaginous endplates (1). When the annulus fibrosus ruptures and the intervertebral disc herniates, the integrity of the annulus fibrosus is compromised and the integrity of the segmental stability is affected (2). Therefore, an important goal in the treatment of intervertebral disc herniation must be tantamount to restore the IVD function and the stability of the motion segment.

Lumbar disc herniation (LDH) is a common disease in spine surgery, which often causes low back pain, radiating pain in the lower extremity, paresthesia and other symptoms, which seriously affect the daily life of patients. Most patients can relieve symptoms by conservative treatment such as traction, non-steroidal anti-inflammatory analgesics, and bed rest. For patients with persistent symptoms, surgery may be the better option, with lumbar discectomy providing faster and longer-lasting relief of radicular pain. In recent years, minimally invasive treatment of LDH has become a research hotspot. Due to its safety and efficacy, percutaneous endoscopic discectomy for LDH is being increasingly accepted by spine surgeons. However, lumbar discectomy is associated with recurrent disc herniation in 3%–18% of patients (3–5), and the reherniation rate is significantly higher for patients with a large annulus fibrosus defect (>6 mm) than for patients with a defect of <6 mm (6). Compared with limited discectomy, excessive discectomy leads to more serious disc degeneration and disc height loss (4, 7). In addition, the risk of reherniation is affected by age and weight (8, 9). Thus, an annulus fibrosus suture following lumbar discectomy is theoretically necessary to reduce reherniation and maintain the height of the intervertebral space. At present, it is very challenging to attain an adequate visual field to suture the annulus fibrosus due to the limited diameter of the endoscope channel (10). We developed a full-endoscopic annulus fibrosus suture device with an anchored wire rod through which the defective annulus fibrosus can be sutured visually under microendoscopy; this technique may reduce the LDH recurrence rate. The present study aimed to retrospectively compare the efficacy of full-endoscopic annulus suture with lumbar discectomy versus conventional lumbar discectomy in the treatment of LDH, and evaluate a novel minimally invasive method to repair the residual annulus fibrosus after discectomy to reduce the risk of recurrence.

Patients and methods

Patient selection

Patients with LDH were retrospectively divided into those who received lumbar discectomy combined with full-endoscopic suture of the annulus fibrosus (LD + AFS group) and those who received conventional lumbar discectomy (LD group). The ethics review board of Xuzhou Central Hospital approved the study. All patients provided written informed consent.

Patients who met the inclusion criteria were treated with full-endoscopic lumbar discectomy combined with annulus fibrosus suture in our department from January 2018 to June 2020. The final cohort comprised 82 patients who were followed up for 18 months.

Inclusion criteria: (1) LDH diagnosed based on CT, MRI, symptoms, and signs, with no response to conservative treatment for 6–12 weeks; (2) no significant lumbar instability in the flexion-extension position on radiography; (3) imaging revealed a soft protrusion or prolapse and no obvious calcification or ossification around the annulus fibrosis; (4) annulus fibrosus defect of <10 mm after discectomy.

Exclusion criteria: (1) spondylolisthesis or segmental lumbar instability; (2) scoliosis of >10°; (3) obvious calcification or ossification around the annulus fibrosis; (4) annulus fibrosus defect of >10 mm after discectomy or paracentral disc herniation and lateral disc herniation without calcification revealed on imaging; (5) Pfirrmann grading of disc degeneration not greater than grade IV; (6) needle insertion point >2 mm from the edge of the annulus fibrosus defect or a defect diameter of <4 mm; (7) acute local or systemic infection; (8) spinal primary tumor or metastatic tumor.

Annulus fibrosus suture device

The annulus fibrosus suture device used in this study is a new product developed and designed on the basis of our previously authorized Chinese utility model patents (patent number: ZL 2017 2 0518470.6). The annulus fibrosus suture device has been approved by the Food and Drug Administration of Beijing, Registeration Certificate No.: Beijing Registeration Approval No. 20182040343. The anchoring device can be absorbed by the body.

Protocol for annulus fibrosus suture placement

Surgery was carried out under normal local anesthesia (2% lidocaine diluted from 10 to 30 ml) with the patient in the genupectoral position. Under C-arm fluoroscopic guidance, a paramedian incision was made over the affected intervertebral space. The process of annulus fibrosus suture following lumbar discectomy was performed as follows. (1) A full endoscope with a 7.0-mm diameter working cannula entered the spinal canal. The nerve root and dorsolateral side of the dural sac were retracted. Free loose nucleus pulposus was removed with nucleus pulposus pliers after the annulus fibrosus defect and nucleus pulposus prolapse were fully exposed. The area was checked to ensure that there was no residue. A radiofrequency plasma electrode was used to shape the nucleus pulposus and annulus fibrosus, and the annulus fibrosus was fully exposed. (2) The annulus fibrosus was sutured under microendoscopy. The threaded puncture needle of the annulus fibrosus suture device was pierced into the annulus fibrosus at the side of the breach with a margin of 2–4 mm. The guidewire pushed the built-in wire rod with anchoring device into the annulus fibrosus, and the needle and guidewire were withdrawn to complete the implantation of the first suture. The other side of the suture rod was then implanted in the annulus fibrosus defect in the same way. Finally, a special endoscopic knot pusher was used to tie the knot to repair the annulus fibrosus defect. To ensure that the knot was securely tied, a surgical knot was used for the first knot, and then two square knots were continuously tied. Excess suture material was cut off after the reliability of the suture was confirmed. When the working cannula was withdrawn to the vertebral plate, the nerve root and dural sac fell back naturally, the tense nerve root relaxed, and the dural sac and nerve root resumed pulsation. The patient was then instructed to cough; if there was no obvious pain, the working cannula was safely removed. The wound was sutured and dressed with sterile auxiliary materials (**Figures 1**, **2**).

Patient-related outcome assessment

Visual analog scale (VAS) pain scores and Oswestry Disability Index (ODI) scores were assessed preoperatively, on postoperative day 3, and 3, 6, 12and 18 months postoperatively. Lumbar MRI and CT were performed 3 and 18 months postoperatively. The Pfirrmann grading system was used to evaluate the lumbar disc degeneration preoperatively and 18 months postoperatively.

Statistical analysis

Quantitative data are presented as the mean and standard deviation. The independent sample *t*-test and χ^2 test were used to compare data between two groups, while analysis of variance and least significant difference tests were used to compare data between multiple groups. Statistical significance was set *a priori* at $p < 0.05$. SPSS 17.0 was used for statistical analysis.

Results

The study cohort comprised 82 patients, including 37 females and 45 males. The average age was 37 years (range 16–59 years). There were no differences between the two groups in baseline data such as age, sex, herniated disc location, and herniation type (**Table 1**). There were no significant differences between groups in the preoperative VAS scores for lumbar pain and lower limb pain, and the ODI scores (**Table 2** and **Figure 3**). The herniation was located at L3–4 in four cases, L4–5 in 42, and L5–S1 in 36. All patients underwent full-endoscopic discectomy through the interlaminar approach. All operations were completed successfully. The average operation time was significantly longer in the LD + AFS group (65.12 ± 4.56 min) than the LD group (54.45 ± 5.62 min, $p < 0.05$). The operation went smoothly in both groups, intraoperative nerve injury, dural tear, or other complications such as postoperative infection, cerebrospinal fluid leakage or aggravation of nerve root function. There was no significant difference in hospitalization days between the two groups ($p < 0.05$). Postoperative lumbar MRI showed complete resection of the herniated disc and adequate nerve decompression in all patients (**Figure 4**). The lumbar disc degeneration at 1 year postoperatively was assessed using the modified Pfirrmann grading system (**Table 3**).

Discussion

Lumbar discectomy is a common spinal surgery. Postoperative symptomatic reherniation means that the patients experience more pain, require a more complicated reoperation, and incur additional complications and more costs (8, 9, 11, 12). A prospective multicenter randomized controlled trial that used the “Xclose” annulus fibrosus repair device to suture the annulus fibrosus defect after lumbar discectomy found that the recurrence rate of the annulus fibrosus suture group was lower than that of the unsutured group at 2 weeks and 6 months postoperatively, while the recurrence rate at 2 years postoperatively did not differ between the two groups (13). Another multicenter randomized controlled trial demonstrated that the use of a bone-anchored annular closure device to close the annulus fibrous gap after lumbar discectomy reduced symptomatic recurrence and the risk of reoperation (8). A multicenter prospective cohort study reported that the use of the “Barricaid” annulus fibrosus closure device resulted in no recurrent disc herniation and effectively maintained the height of the intervertebral disc and improved leg, back, and lumbar pain for 1 year (14). Cho et al. (15) reported that the reherniation rate after annulus fibrosus suture (3.3%) was

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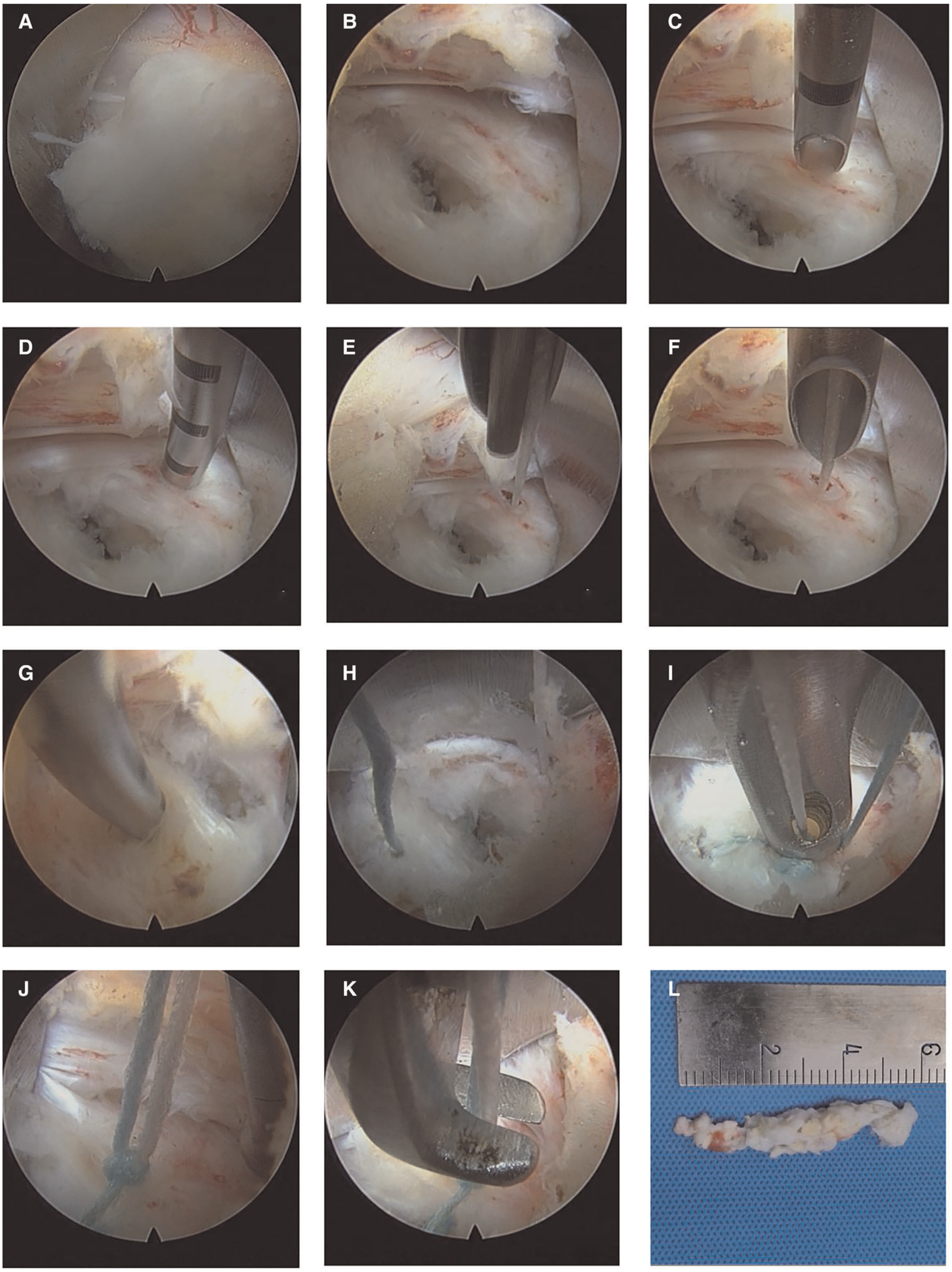

FIGURE 1
Intraoperative visualization of the annulus fibrosus suture process. (A) Exposure of the protruding nucleus pulposus *via* the interlaminar approach. (B) Excision of the nucleus pulposus reveals the damaged annulus fibrosus and an annulus fibrosus defect of about 5 mm. (C,D) The suture needle is inserted into the healthy annulus fibrosus 5 mm from the defect. (E,F) The guide-needle is used to push in the white suture with the anchoring device. (G,H) The same method is used to place blue sutures in the lateral healthy annulus fibrosus. (I,J) Placement of the knotted bilateral anchor line. (K) Suture cutting. (J) Excised nucleus pulposus.

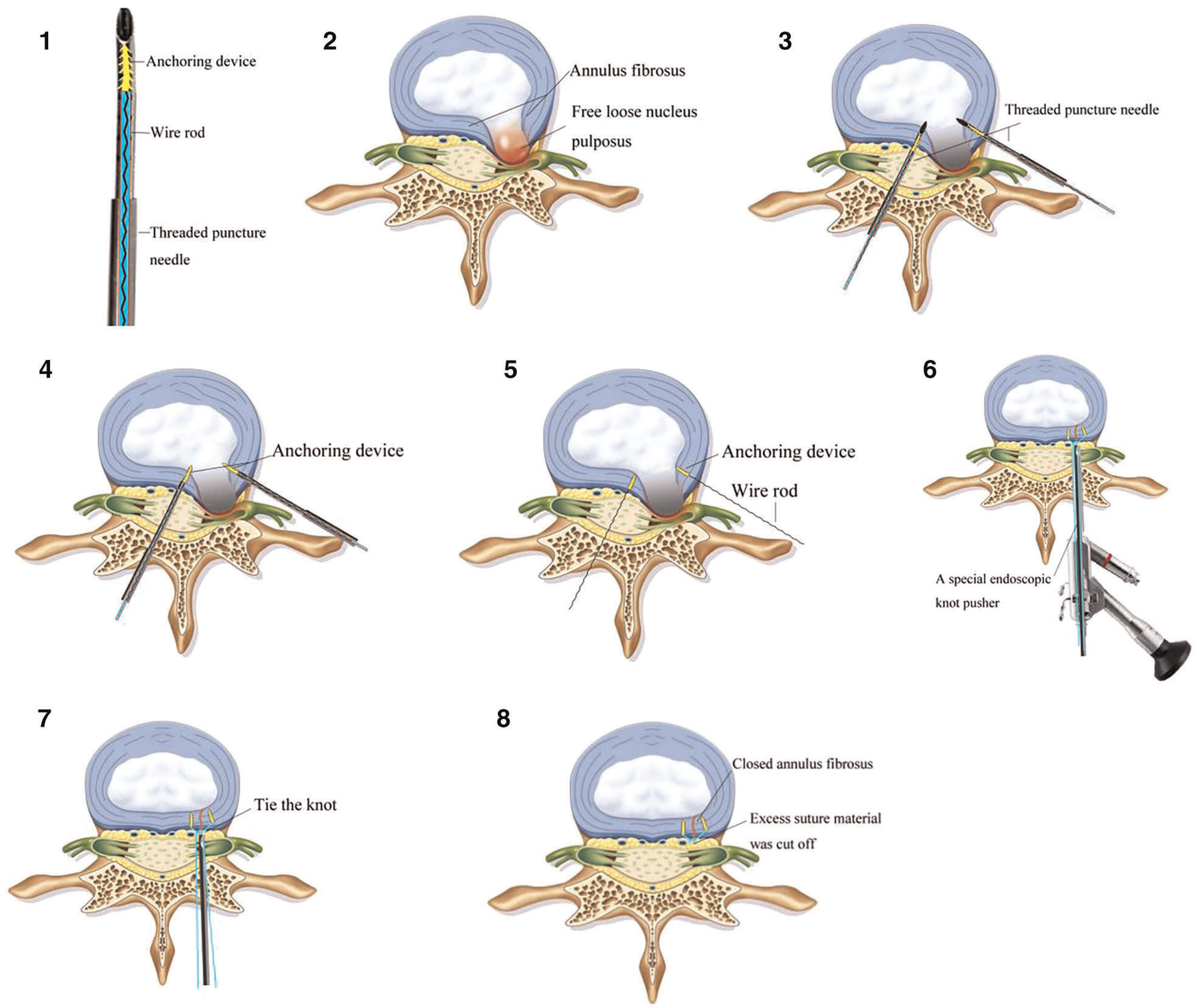

FIGURE 2
The diagrammatic drawing of the annulus fibrosus suture process. 1. The threaded puncture needle of the annulus fibrosus suture device. 2. The free loose nucleus pulposus. 3. The threaded puncture needle of the annulus fibrosus suture device was pierced into the annulus fibrosus at the bilateral breach. 4. The guidewire pushed the built-in wire rod with anchoring device into the annulus fibrosus. 5. The guidewire pushed the built-in wire rod with anchoring device into the annulus fibrosus, and the needle and guidewire were withdrawn to complete the implantation of the suture. 6–7. A special endoscopic knot pusher was used to tie the knot to repair the annulus fibrosus defect. 8. Excess suture material was cut off.

significantly lower than that after traditional discectomy (20%); however, the relatively small sample size limited the ability to extrapolate their results to a larger population. Overall, these previous findings suggest that lumbar discectomy combined with annulus fibrosus suture has positive clinical significance.

It is difficult to suture the annulus fibrosus under full endoscopy. Li et al. (10) reported the technical points and clinical effects of annulus fibrosus suture under full endoscopy. However, in the absence of a control group, it remains unclear whether full-endoscopic annulus fibrosus suture significantly reduces the LDH recurrence rate. In our surgical experience, the limitations of the diameter of the working channel of the endoscopic system and the size of the stapler mean that non-visual annulus fibrosus suture placement carries a risk of damaging the fragile nerve roots. Therefore, our team used full endoscopy to fully visualize the annulus fibrosus defect, complete the anchoring and implantation of the first and second stitches, knot the sutures, and cut the sutures under direct vision. This process can be done using conventional endoscopy, which is widely available. In this study, the interlaminar approach was used in all patients because the translaminar approach was more intuitive than the intervertebral foraminal approach, the annulus fibrosus rupture was more clearly exposed, and it was easier to suture the annulus fibrosus under the endoscope. The 40 patients who underwent total endoscopic lumbar discectomy

TABLE 1 Baseline data.

	LD + AFS	LD	*p*-value
Gender			
M	22	23	
G	18	19	
Operation level			
L3/4	1	3	
L4/5	20	22	
L5/S1	19	17	
No. of reoperations	0	3	
Hospitalization day (Day)	7.0 ± 1.60	7.21 ± 1.77	<0.05
Operation time (min)	65.12 ± 4.56	54.45 ± 5.62	>0.05

LD + AFS, full-endoscopic annulus fibrosus suture following lumbar discectomy; AFS, annulus fibrosus suture.

combined with annulus fibrosus sutures had no intraoperative adverse events, reflecting the overall safety of the operation. During the operation, the annulus fibrosus was preserved as much as possible because most of the annulus fibrosus can be repaired by itself or *via* scarring. Furthermore, less nucleus pulposus resection is conducive to maintaining the height of the intervertebral space (4, 14). However, it was unclear whether excessive resection of the nucleus pulposus reduced the recurrence of LDH. Although recurrence after discectomy is related to many factors (16), our experience suggests that the free and loose nucleus pulposus should be removed as much as possible to reduce the risk of recurrence in the short term. Annulus fibrosus sutures are mainly used to restore the integrity of the annulus fibrosus, but do not improve the disc degeneration in some patients. In addition, the remaining knot raises concerns about potential nerve irritation; however, this did not happen after surgery in the present study, There was no significant difference in ODI, VAS score of low back pain and VAS score of lower extremity pain between the two groups before and after operation. The patients in both groups obtained good clinical efficacy and the preserved knot did not show nerve irritation symptoms, possibly because of the softness of the suture material. We found that suture placement under microendoscopic visualization had a steep learning curve, and the operation time was longer in the LD + AFS group than the LD group. The longer operation time was associated with the increased time required for the suture procedure. However, we observed a gradual reduction in operation time as the proficiency with the procedure increased. During a follow-up period of 18 months, the symptomatic reherniation rate was significantly higher in the LD group (7.14%, 3/42) than the LD + AFS group (0%, 0/40). Within 6 months postoperatively, three patients in the LD group had imaging and symptomatic recurrence; two of these patients had recurrence due to weight-bearing 1 month postoperatively, which might be related to the failure of the annular fibrosus repair. Studies have shown that the mechanical strength of annulus fibrosus healing scars is still significantly lower than that of normal annulus fibrosus tissue (17). The lumbar pain, leg pain, and ODI scores were significantly improved postoperatively in both groups.

TABLE 2 Pre- and postoperative VAS and ODI scores of the two groups.

Index	Time	LD + AFS	AFS	T value	*p*-value
VAS back pain	Preop	3.12 ± 1.30	3.40 ± 1.41	0.771	0.446
	Postop 3d	1.22 ± 0.58	1.40 ± 0.59	0.530	0.599
	Postop 3m	1.10 ± 0.59	1.02 ± 0.51	−0.530	0.599
	Postop 6m	0.88 ± 0.55	0.70 ± 0.51	−1.433	0.160
	Postop 12m	0.50 ± 0.51	0.67 ± 0.47	−0.443	0.660
	Postop 18m	0.41 ± 0.46	0.52 ± 0.53	−1.226	0.281
	p-value	<0.001	<0.001		
VAS leg pain	Preop	5.22 ± 1.75	5.70 ± 1.66	0.183	0.855
	Postop 3d	1.02 ± 0.70	1.11 ± 0.71	0.206	0.838
	Postop 3m	0.67 ± 0.57	0.57 ± 1.02	−0.940	0.352
	Postop 6m	0.42 ± 0.50	0.50 ± 0.55	−0.443	0.66
	Postop 12m	0.32 ± 0.50	0.42 ± 0.55	1.443	0.160
	Postop 18m	0.22 ± 0.39	0.36 ± 0.43	−0.526	0.781
	p-value	<0.001	<0.001		
ODI	Preop	61.40 ± 13.31	57.5 ± 13.49	1.589	1.120
	Postop 3d	9.22 ± 3.31	10.05 ± 3.21	−0.625	0.536
	Postop 3m	8.02 ± 2.72	9.12 ± 2.71	−1.275	0.21
	Postop 6m	7.50 ± 2.53	8.67 ± 2.39	0.206	0.838
	Postop 12m	6.75 ± 2.33	7.11 ± 2.57	0.628	0.534
	Postop 18m	5.22 ± 1.97	5.46 ± 2.53	−1.122	0.267
	p-value	<0.001	<0.001		

Values are presented as mean ± standard deviation. LD + AFS, full-endoscopic annulus fibrosus suture following lumbar discectomy; AFS, annulus fibrosus suture; VAS, visual analog scale; ODI, Oswestry Disability Index; Preop, preoperative; Postop, postoperative; Postop 3d, postoperative day 3; Postop 3m, 3 months postoperatively; Postop 6m, 6 months postoperatively; Postop 12m, 12 months postoperatively; Postop 18m, 18 months postoperatively.

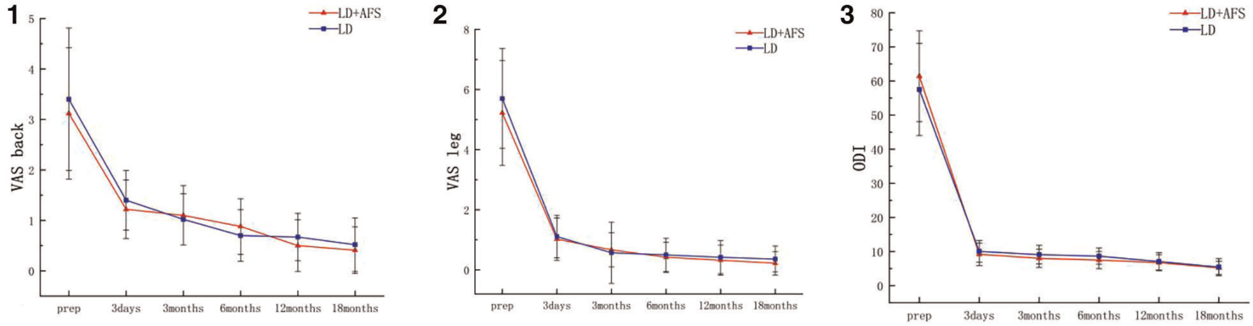

FIGURE 3
Changes in the visual analog scale (VAS) pain scores for the back (1) and leg (2), and in the Oswestry Disability Index (ODI) (3). LD + AFS: full-endoscopic annulus fibrosus suture following lumbar discectomy, AFS: annulus fibrosus suture.

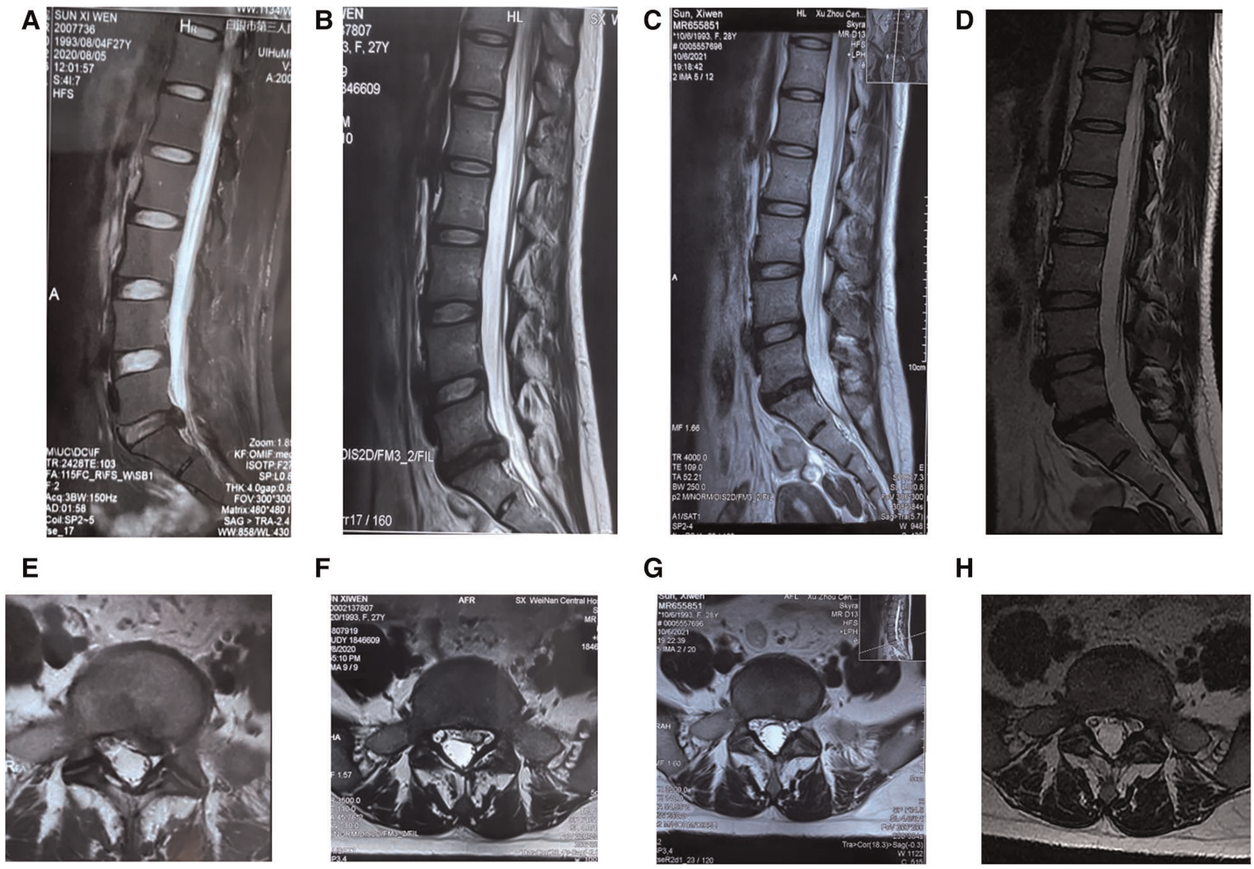

FIGURE 4
MRI of a 27-year-old woman with lumbar disc herniation with L5/S1 left center prolapse who was treated with full endoscopic nucleus pulposus resection combined with annulus fibrosus suture. (A,E) Preoperative sagittal and horizontal MRI showing grade III disc degeneration, compression and deformation of the dural sac, and compression of the right nerve root. (B,F) MRI at 3 months postoperatively shows the absence of prominent nucleus pulposus, no compression of the dura, and no obvious stenosis of the lateral recess. (C,G) MRI at 1 year postoperatively shows no significant disc herniation. (D,H) MRI at 18 months postoperatively shows the same as at 1 year.

TABLE 3 Modified Pfirrmann grade of disc degeneration in the two groups.

	LD + AFS				LD					
	I	II	III	IV	I	II	III	IV	X^2	p
Preop	0	1	23	16	0	0	27	15	0.061	0.836
Postop 18 m	4	6	17	13	2	7	20	13	0.263	0.623
X^2	7.633				8.241					
p	0.026				0.039					

LD + AFS, full-endoscopic annulus fibrosus suture following lumbar discectomy; AFS, annulus fibrosus suture; Preop, preoperative; Postop 18m, 18 months postoperatively.

Full-endoscopic lumbar discectomy is a minimally invasive surgery that has broad appeal for both patients and surgeons. However, the technique of annulus fibrosus suture under full endoscopy is still challenging. Our novel device enables the annulus fibrosus suture to be completed under conventional small-channel endoscopy. Our study demonstrated that full-endoscopic annulus fibrosus suture is safe, reliable, and effective, reducing the risk of reprotrusion and reoperation during 18 months of follow-up. However, the present study has some limitations. Firstly, the suture technique has a long learning curve. Secondly, only a limited number of cases were followed up, and the follow-up time was relatively short. The present results require confirmation in a long-term multicenter study with a large sample size. We plan to conduct a future study with a longer follow-up duration and larger sample size.

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

The studies involving human participants were reviewed and approved by the Ethics Committee of Xuzhou Central Hospital. 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

GWL, CM, JL and KRD contributed to conception and design of the study. LX and JHB organized the database. MJX and TC performed the statistical analysis. ZFW wrote the first draft of the manuscript. SH, GWL, LX, and GPL wrote sections of 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 in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Posterior hemivertebra resection without internal fixation in the treatment of congenital scoliosis in very young children

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Objective: To retrospectively analyze the feasibility and efficacy of posterior hemivertebra resection without internal fixation in the treatment of congenital scoliosis in very young children.

Methods: Sixteen cases of very young children with congenital scoliosis treated at our hospital from April 2000 to July 2019 were collected, including 8 cases of each sex, all of whom had type I/III congenital scoliosis and were operated on at a median (interquartile range) of 9.00 (7.75) months (range, 0.5–48 months) of age. All cases underwent posterior hemivertebra resection without internal fixation and wore orthopedic braces or plaster undershirts for more than six months after surgery, with a mean follow-up of 94.31 ± 65.63 months (range, 36–222 months).

Results: Coronal plane: the preoperative Cobb angle for the segmental curve was 39.50 ± 9.70° compared to postoperative (19.19 ± 8.56°) and last follow-up (14.94 ± 12.11°) (both $P < 0.01$); the preoperative Cobb angle for the main curve was 34.19 ± 14.34° compared to postoperative (17.00 ± 11.70°) and last follow-up (17.56 ± 16.31°) (both $P < 0.01$); the preoperative Cobb angle of the proximal compensated curve was 14.88 ± 9.62° compared to postoperative (7.88 ± 4.66°) and last follow-up (8.38 ± 8.36°) (both $P < 0.05$); and the preoperative Cobb angle of the distal compensated curve was 13.50° (10.50°) (range, 4°–30°) compared with postoperative 4.50° (9.25°) (range, –3° to 25°) and final follow-up 5.50° (9.50°) (range, –3° to 33°) (both $P < 0.01$). Sagittal plane: the difference in the preoperative Cobb angle was 10.00° (14.00°) (range, –31° to 41°) for segmental kyphosis compared to postoperative 14.00° (24.50°) (range, –6° to 46°) and last follow-up 17.00° (22.55°) (range, –40° to 56°), and these were not statistically significant (both $P > 0.05$). There was a tendency for the thoracolumbar kyphosis to worsen and the lumbosacral kyphosis to improve during the follow-up period.

Conclusion: Posterior hemivertebra resection without internal fixation is a feasible treatment for type I/III congenital scoliosis in very young children, but the correction of the sagittal deformity of the thoracolumbar spine is not satisfactory, and postoperative external fixation may require further improvement.

KEYWORDS

spinal surgery, hemivertebra resection, young children, x-ray, computer tomography

Introduction

Congenital scoliosis is a congenital abnormality of vertebral segment development due to various causes, and congenital scoliosis gradually induces an imbalance in the coronal and/or sagittal planes of the spine during spinal growth, which in turn produces a three-dimensional deformity of the spine (1–3). The incidence of congenital scoliosis in the general population is approximately 1/1,000 to 1/2,000, and the incidence is greatly affected by environmental and genetic factors (4). There are three types of congenital scoliosis (5): Type I: vertebral body formation disorders, including hemivertebrae, butterfly vertebrae, cuneiform vertebrae, etc.; Type II: vertebral body segmentation disorders, including bony bridges, massive vertebra, block vertebrae, etc.; and Type III: mixed type, in which one vertebral body segmentation disorder is combined with a contralateral vertebral body formation disorder. The most common hemivertebral deformity is caused by abnormal unilateral vertebral body formation (6), and fully segmented hemivertebrae and type III congenital scoliosis have early onset and rapid progression (1). Conservative treatment cannot prevent deformity progression, and some researchers recommend early surgical intervention (7–9). Early surgery in young children with congenital scoliosis can slow down or prevent further development of the deformity, thus allowing the unaffected part of the spine to grow normally (2). Although posterior hemivertebra resection combined with pedicle screw internal fixation is effective, children can experience complications such as pedicle fracture and internal fixation prolapse (10–13), and it is difficult to choose suitable internal fixation screws for very young children. Posterior hemivertebra resection without internal fixation can avoid the complications associated with internal fixation, but there are few reports about this kind of treatment. Therefore, this study was performed to evaluate the feasibility and efficacy of posterior hemivertebra resection without internal fixation for congenital scoliosis in very young children.

Methods

Patients

This was a retrospective analysis of 16 young children (8 males and 8 females) with congenital scoliosis who were not treated with internal fixation devices after posterior hemilaminectomy at our institution from April 2000 to July 2019, all of whom had type I/III congenital scoliosis. The age at presentation of the patients was a median (interquartile range) of 9.00 (7.75) months (range, 0.5–48 months), and there were 11 cases with clear indications of scoliosis at presentation, 7 cases with an abnormal mass on the back, 4 cases of asymmetry of the lower limbs, 5 cases of abnormal hair on the waist and back, 2 cases of hallux valgus or eversion, and 3 cases of dysuria.

The following tests were completed before surgery: full spine frontal and lateral x-rays in both straight and bent positions to comprehensively assess the static parameters and flexibility of the spine, computer tomography scan and 3D reconstruction to assess the morphology and position of the hemivertebral body and adjacent vertebral bodies as well as the anatomy of the pedicle and posterior vertebral body, magnetic resonance imaging and bilateral lower extremity electromyography to exclude neurological disorders, and echocardiography to assess relevant congenital anomalies.

Study methods

All operations were performed by the same specialist with extensive experience in the treatment of congenital scoliosis. The operative site, operative time, intraoperative blood loss, and follow-up time were collected; and the Cobb angles of the segmental curve, main curve, proximal compensatory curve, distal compensatory curve, and segmental kyphosis were measured on preoperative, postoperative, and final follow-up frontal and lateral radiographs of the children.

Surgical procedure

All patients underwent posterior hemivertebrectomy with unilateral hemivertebra exposure in type I scoliosis and bilateral exposure in type III. No spinal instrumentation was used after simple hemivertebra resection.

Under general anesthesia, the patient was placed in the prone position. Positioned with the C-arm and marked, the posterior aspect of the spine was exposed unilaterally at the level of the hemivertebrae and adjacent vertebrae using a standard median incision. The paravertebral muscles were stripped to expose the small joints, laminae, and spinous processes above and below the hemivertebral body, and the extranodal and anterior periosteum of the hemivertebral body were stripped. The posterior portion of the ipsilateral hemivertebral body was excised, including the laminae with transverse process, the facet joints, and the posterior part of the pedicle of the vertebral arch. If the hemivertebra was located in the thoracic segment, the posterior corner of the rib connected with the hemivertebra to the part of the rib capitulum was also removed taking care to avoid damaging the parietal pleura, and the broken end of the rib was closed with bone wax. In the event of epidural bleeding during the operation, bipolar electrocoagulation hemostasis was performed. The spinal cord and the nerve roots above and below the hemivertebrae were carefully separated and protected with cotton sheets, and the residue of the hemivertebral body and adjacent intervertebral discs was scraped off. The endplates of the convex side of the vertebral body were removed up to the cancellous bone, and the opposite end plate was preserved. Autologous and allogeneic bone blocks were implanted at the hemivertebral body resection. In cases of contralateral bone bridging, unilateral exposure was inadequate and bilateral exposure was required to sever the bone bridge and remove the fused rib head. Motor evoked potential and somatosensory evoked potential were monitored during the operation.

An orthopedic brace or plaster vest was applied immediately after surgery. For infants who could not walk, they stayed in bed with braces or plaster vests for 3 weeks after surgery, and after that they could sit and be held upright. For children who could walk, they could get out of bed and walk three weeks after surgery, but strenuous exercise was to be avoided. All children wore an orthopedic brace or plaster vest all day for the first 3 months after surgery. After 3 months, if osseous fusion had occurred, the brace could be worn during the day and removed at night. During the 6-month follow-up period, the plaster and orthopedic braces were timely adjusted or replaced according to the growth rate of the children.

Statistical analysis

SPSS 25.0 software was used for statistical analysis. Preoperative, postoperative, and final follow-up data were analyzed by the Wilcoxon signed-rank test or paired *t*-test. Data that had a normal distribution are presented as the mean ± standard deviation, and measures that did not conform to a normal distribution are presented as the median (interquartile range.). Differences were considered statistically significant at $P < 0.05$.

Results

The 16 children (8 males and 8 females) all had type I/III congenital scoliosis with a single hemivertebral deformity, and 7 cases were combined with spinal cord tethering syndrome, 2 cases with spinal cord cavity, 5 cases with spinal cord longitudinal bifida, 3 cases with spondylolisthesis, and 1 case with spina bifida. A total of 16 hemivertebrae were resected, of which 3 were located in the main thoracic segment (T6–T9), 9 in the thoracolumbar segment (T10–L2), 3 in the lumbosacral segment (L3–S1), and 1 in the sacral segment (S2–S5). The age at surgery was 9.00 (7.75) months (range, 0.5–48 months), the mean postoperative follow-up time was 94.31 ± 65.63 months (range, 36–222 months), the mean operative time was 119.88 ± 37.93 min (range, 65–195 min), and the mean bleeding volume was 95.6 ± 56.78 ml (range, 40–250 ml) (Table 1).

Coronal plane

The differences between the preoperative Cobb angle of the segmental curve (39.50 ± 9.70°) and the postoperative (19.19 ± 8.56°) and final follow-up (14.94 ± 12.11°) angles were both statistically significant ($P < 0.001$ and $P = 0.001$, respectively) (Table 2). The mean correction rates postoperatively and at final follow-up were 49.98% and 62.09%, respectively. During the follow-up period, 12 (75%) patients showed sustained improvement in the segmental curve (Figure 1).

The differences between the preoperative Cobb angle of the main curve (34.19 ± 14.34°) and the postoperative (17.00 ± 11.70°) and the last follow-up (17.56 ± 16.31°) angles were both statistically significant ($P < 0.001$ and $P = 0.005$, respectively) (Table 2). The mean correction rates postoperatively and at last follow-up were 53.22% and 46.93%, respectively, and in 11 (68.75%) cases the patients showed sustained improvement of the principal curve during the follow-up period (Figure 2).

The differences between the preoperative Cobb angle of the proximal compensated curve (14.88 ± 9.62°) and the postoperative (7.88 ± 4.66°) and the last follow-up (8.38 ± 8.36°) angles were statistically significant ($P = 0.002$ and $P = 0.012$, respectively), and the mean correction rates postoperatively and at last follow-up were 34.46% and 33.89%, respectively. The differences between the preoperative Cobb angle of the distal compensated curve 13.50° (10.50°) (range, 4°–30°) and the postoperative 4.50° (9.25°) (range, −3° to 25°) and last follow-up 5.50° (9.50°) (range, −3° to 33°) angles were statistically significant ($P = 0.001$ and $P = 0.007$, respectively), and the mean postoperative and last follow-up correction rates were 61.11% and 51.88%, respectively (Table 2).

Sagittal plane

There was no statistically significant difference in the preoperative Cobb angle 10.00° (14.00°) (range, −31° to 41°) for segmental kyphosis compared with the postoperative 14.00° (24.50°) (range, −6° to 46°) and the final follow-up 17.00° (22.55°) (range, −40° to 56°) angles ($P = 0.109$ and $P = 0.408$, respectively), and the mean postoperative and last follow-up correction rates were 2.44% and 51.86%, respectively (Table 2).

Complications and reoperation

There were no exacerbations of neurological symptoms, no infections, and no cerebrospinal fluid leakage after surgery in any patient. During the follow-up period, 3 cases had loss of curve correction due to residual hemivertebrae: 1 case

TABLE 1 Clinical data of the included patients.

Case	Age (months)	Sex	Hemivertebra position	Type	Operation time (min)	Volume of bleeding (ml)	Follow-up time (months)	Final correction rate of the segmental curve (%)
1	10	M	T8	I	120	80	197	47.2
2	6	F	T10	I	160	150	48	75.0
3	3	M	S1	I	85	60	55	93.5
4	4	F	T9	III	120	40	36	69.0
5	18	M	L2	I	75	60	39	70.8
6	5	F	L1	III	120	100	38	66.0
7	0.5	M	L5	I	65	50	145	77.4
8	12	M	L3	I	65	50	191	84.4
9	5	F	L2	I	165	120	126	−13.5
10	48	F	T11	III	195	100	55	61.7
11	30	F	S2	I	135	120	222	90.9
12	12	M	T11	I	115	70	127	44.7
13	2	M	L1	I	142	60	38	52.3
14	9	F	T10	I	113	175	36	93.3
15	11	F	T11	I	88	50	108	−5.6
16	9	M	T6	I	155	250	48	86.2

M, male; F, Female.

TABLE 2 Preoperative, postoperative, and last follow-up radiographic imaging parameters of children with congenital scoliosis who underwent posterior hemivertebral resection without internal fixation.

Parameters	Preoperative	Postoperative	Final follow-up	P (Preoperative vs. Postoperative)	P (Preoperative vs. Final follow-up)
Coronal plane					
Segmental curve (°)	39.50 ± 9.70	19.19 ± 8.56	14.94 ± 12.11	<0.001	0.001
Main curve (°)	34.19 ± 14.34	17.00 ± 11.70	17.56 ± 16.31	<0.001	0.005
Proximal compensatory curve (°)	14.88 ± 9.62	7.88 ± 4.66	8.38 ± 8.36	0.002	0.012
Distal compensatory curve (°)	13.50 (10.50)	4.55 (9.25)	5.50 (9.50)	0.001	0.007
Sagittal plane					
Segmental kyphosis (°)	10.00 (14.00)	14.00 (24.50)	17.00 (22.55)	0.109	0.408

The data are shown as the mean ± standard deviation or as the median (interquartile range).

(case 2) had increased sagittal segmental kyphosis (**Figure 3**), 1 case (case 9) had progressive aggravation of the proximal compensatory curve, and 1 case (case 12) had progressive aggravation of the main curve. In addition, 1 case (case 15) had local pain due to local pseudarthrosis formation (**Figure 4**), and scoliosis was progressively aggravated at the follow-up. All of the patients with complications were treated with secondary internal fixation surgery.

Discussion

Hemivertebral deformity is one of the most common causes of congenital scoliosis, and its severity depends on four main factors, namely the type, the location and number of hemivertebrae, their relationship with each other, and the age of the patient (2, 14). Most hemivertebrae have normal growth plates, especially fully

 10.3389/fsurg.2022.1018061

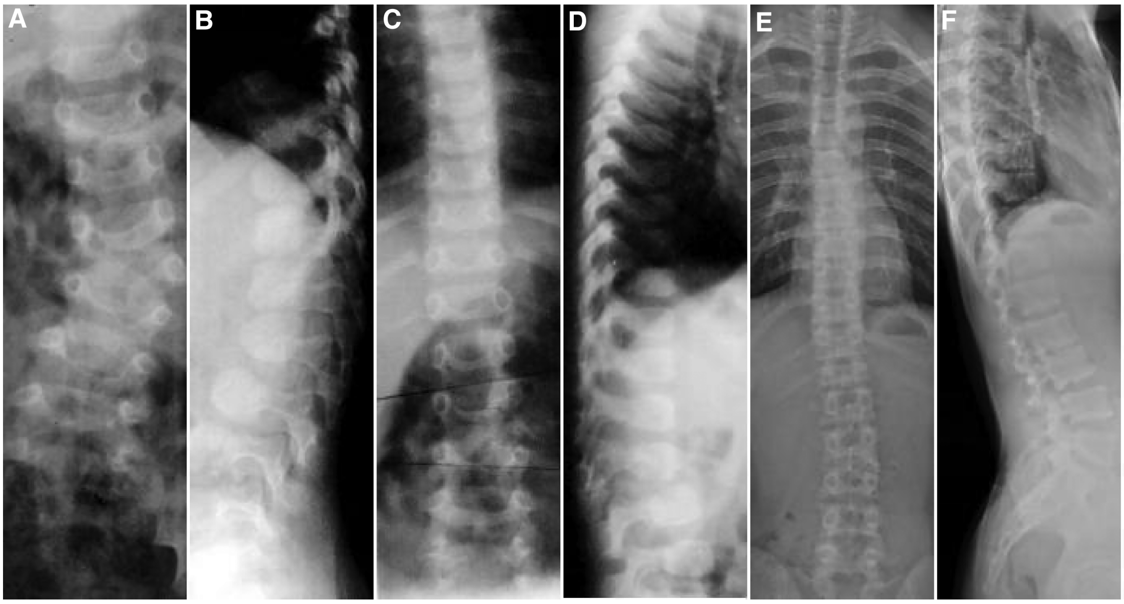

FIGURE 1
Case 8, Male, 12 months old. Preoperative orthogonal (A) and lateral (B) x-ray images showing the left hemivertebrae of L3. Intraoperative hemivertebral resection was performed *via* the posterior approach, and postoperative orthogonal (C) and lateral (D) x-rays are shown. At the follow-up at 15 years and 11 months, the orthogonal (E) and lateral (F) x-rays showed satisfactory correction of the coronal and sagittal deformity with no loss of curve correction.

segmented and non-integrated hemivertebrae, and thus have growth potential similar to that of normal vertebrae (2, 15), and therefore the scoliosis deformity progressively worsens with further spinal growth. If left untreated, the principal curve will gradually increase to more than 41° in approximately 85% of patients (15). For scoliosis caused by

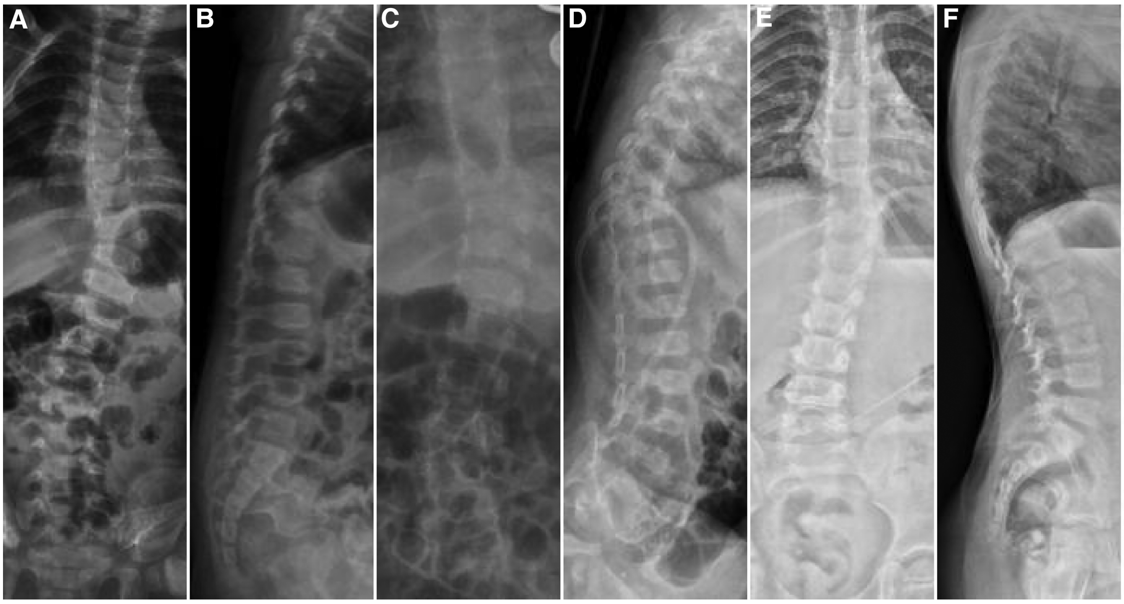

FIGURE 2
Case 14, female, 9 months old. Preoperative orthogonal (A) and lateral (B) x-rays showing the left hemivertebrae at T10. Intraoperative hemivertebra resection was performed *via* the posterior approach, and postoperative orthogonal (C) and lateral (D) x-rays are shown. At 3 years of follow-up, the orthogonal (E) and lateral (F) x-rays showed good correction of the coronal and sagittal deformity.

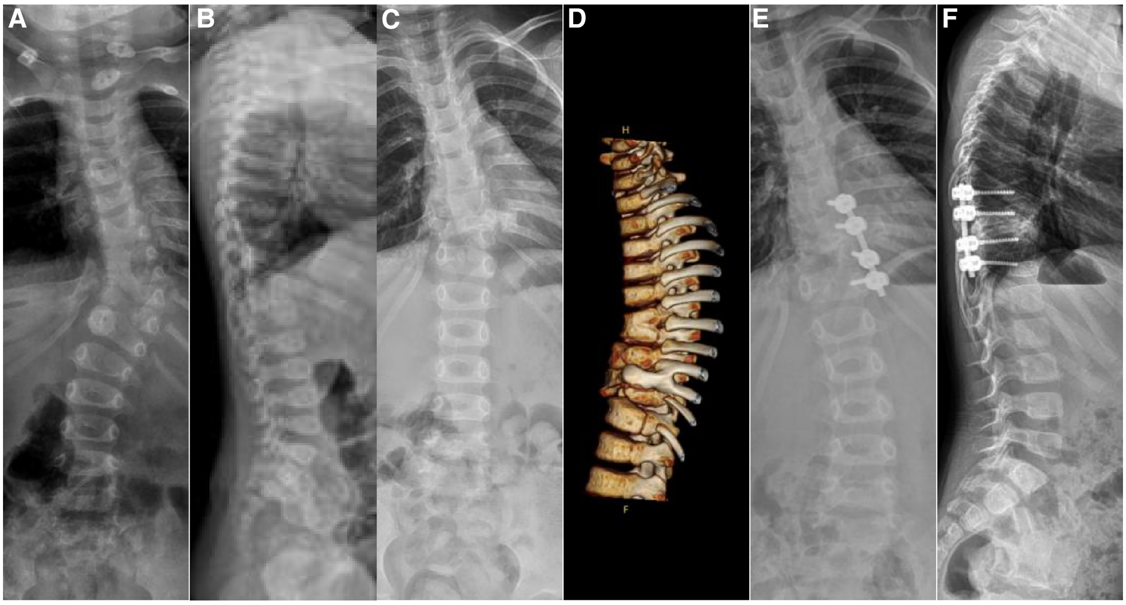

FIGURE 3
Case 2, female, 6 months old. Preoperative orthogonal (A) and lateral (B) x-ray showing the left hemivertebrae of T10. Intraoperative hemivertebra resection was performed *via* the posterior approach. After 4 years of follow-up, orthogonal x-ray (C) and lateral computer tomography (D) showed good correction of coronal scoliosis, but sagittal kyphosis was aggravated, and a second internal fixation revision surgery was performed. Post-revision orthogonal (E) and lateral (F) x-ray showed good correction of the coronal and sagittal deformity.

hemivertebrae, conservative treatment such as bracing is not effective, so surgery is often used for orthopedic treatment (16, 17).

Surgical modalities for the treatment of congenital scoliosis include posterior *in situ* fusion, anterior-posterior convex epiphyseal block, subcutaneous bracing on the concave side of

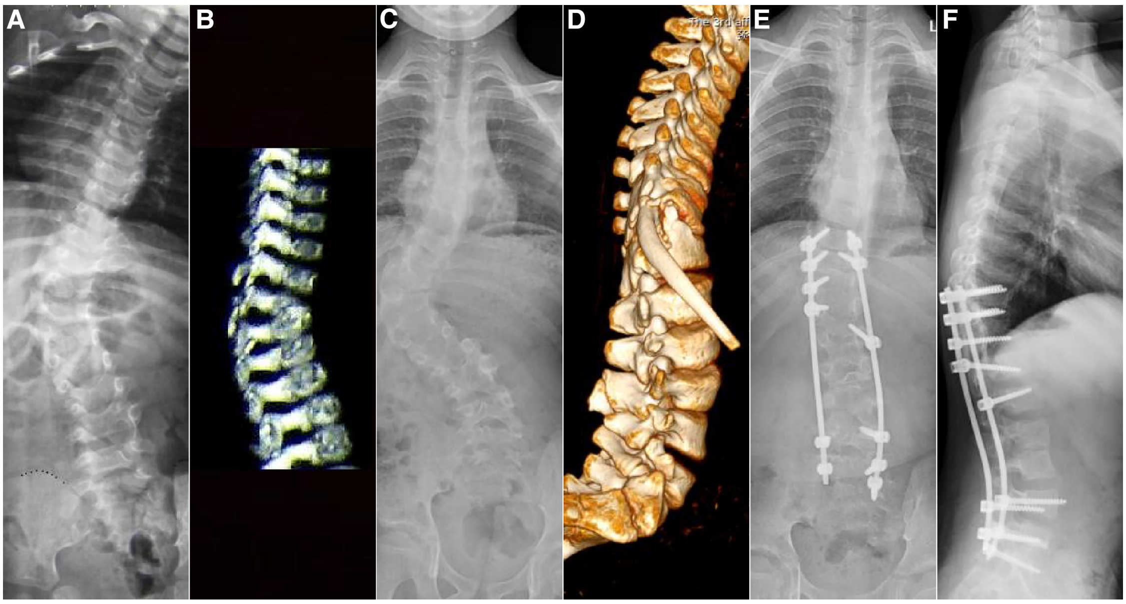

FIGURE 4
Case 15, female, 11 months old. Preoperative orthogonal x-ray (A) and lateral computer tomography (B) showing the right hemivertebrae of T11. Intraoperative hemivertebra resection was performed *via* the posterior approach. After 9 years of follow-up, orthogonal x-ray (C) and orthogonal computer tomography (D) showed local pseudoarticular formation and worsening deformity, and a second internal fixation revision surgery was performed. Post-revision orthogonal (E) and lateral (F) x-ray showed good correction of the deformity in the coronal and sagittal planes.

10.3389/fsurg.2022.1018061

the convex epiphyseal block, and hemivertebrectomy (18). For congenital scoliosis secondary to hemivertebral deformity, posterior hemivertebrectomy is preferred (10, 19, 20). The age at which the patient should undergo surgery is controversial, but there is a greater consensus that surgery before 3 years of age yields better outcomes (1, 14, 19, 21, 22). The goal of early surgery is to maximize the correction of the deformity, prevent the progression of scoliosis, shorten the fused vertebral segments, and reduce the impact on spinal growth before decompensatory structural changes can occur in the spine (23). Young children with good flexibility and only mild primary deformities require only short-segment fusion, which is less difficult to perform, poses less risk of neurological injury, and can achieve better immediate orthopedic results (22). In this study, the median age of the 16 children at surgery was 9 months, and the results at the last follow-up showed that the mean angular correction rates of the segmental and principal curve in the coronal plane were 62.09% and 46.93%, respectively. A total of 12 (75%) cases of segmental curve and 11 (68.75%) cases of main curve saw continuous improvement, which indicated that the children in this age group could tolerate the operation and obtain a certain corrective effect in the coronal plane of the spine, thus avoiding further aggravation of the deformity in most of the children studied here.

Hemivertebrectomy with short segment fixation and fusion has now become the mainstream treatment for congenital scoliosis caused by a single hemivertebra, and the application of pedicle screws can significantly improve the correction rate of congenital scoliosis (24, 25). Although studies have demonstrated that the pedicle screw system is safe and effective in pediatric patients (12, 26), the pedicle is not well developed in very young children (11, 25). Especially for children under 5 years old, it is difficult to maintain a good internal fixation position (20), and the failure of internal fixation implantation is a challenge for hemivertebrectomy in young children (27), mainly including complications such as pedicle fracture and internal fixation prolapse (10–13). In 2003, Ruf et al. (12) reported that among children under 6 years of age who underwent posterior hemivertebrectomy with transpedicular instrumentation, 3 out of 28 had failed internal fixation and 2 out of 28 had pedicle fractures. In 2013, Wang et al. (27) reported that of 36 children with a mean age of 4 years and 11 months, 2 had pedicle overload and fracture, suggesting revision surgery. A study by Guo et al. (11) in 2016 showed a complication rate of 9.5% in 116 posterior hemivertebrectomies, of which 63.6% were related to implantation. Other reports in the literature have shown that congenital scoliosis revision surgery is mostly due to the failure of internal fixation (27) or the inappropriate choice of surgical approach (28). Very young children are sometimes less likely to have access to well-suited internal fixation devices because of their own bone developmental characteristics (20). Because there are no suitable internal fixation screws for use in these very young patients, internal fixation cannot be applied to these children who require treatment. Therefore, the most effective fixation after hemivertebrectomy in order to avoid further worsening of the deformity in younger children with congenital scoliosis needs to be determined.

In 1945, Smith–Peterse (29) first reported the use of posterior lumbar osteotomy for spinal deformities with good postoperative results using plaster undershirt fixation, and this provided a theoretical basis for not using internal fixation after posterior hemivertebrectomy in younger children. Our results showed that early posterior hemivertebrectomy without internal fixation in younger children achieved certain therapeutic results while avoiding complications related to internal fixation, and continued postoperative orthopedic bracing helped to maintain the orthopedic effect and control the progression of the deformity and no complications related to spinal cord injury were observed during the longer follow-up. The results of this study also showed that this surgical approach was effective in correcting coronal deformities, and the difference was statistically significant, but the correction of sagittal kyphosis was not significant. In fact, the thoracic and thoracolumbar kyphosis tended to be aggravated during the follow-up period, especially the thoracolumbar kyphosis, suggesting that the operation may not be suitable for thoracic and thoracolumbar hemivertebral deformities. Four of the patients underwent secondary surgical treatment during follow-up, and three of them (cases 2, 9, and 12) lost their orthopedic effect due to incomplete removal of the hemivertebrae and one (case 15) had an increased deformity in the coronal and sagittal planes due to the formation of local pseudarthrosis. Therefore, complete resection of the bone from the half vertebral body to the upper and lower vertebral bodies was necessary to prevent the aggravation of the deformities and the formation of pseudarthrosis.

Limitations

The small number of patients in this study limited the comparison and statistical analysis of surgical outcomes between different vertebral segments. Furthermore, some of the very young patients did not cooperate well with postoperative treatment, which may have influenced the curve correction during the follow-up period. In addition, the follow-up time in some cases was short and the curve correction of these children may change in future follow-up. Increased numbers of cases and the extension of follow-up time will be helpful in further evaluating the long-term effect after surgery.

Conclusion

In conclusion, posterior hemivertebral resection without internal fixation is a feasible treatment for type I/III congenital scoliosis in very young children. The exposure of posterior,

10.3389/fsurg.2022.1018061

unilateral, and short segments during the operation has the advantages of less trauma and less bleeding, which can effectively delay or prevent the development of more serious structural deformities of the spine, maintain the range of motion of the spine, and effectively reduce hospitalization costs and internal fixation-related complications. Postoperative bracing or several plaster fixations are required to assist in the orthopedic process, resulting in higher correction rates and delaying the age of spinal fusion surgery. This procedure is particularly suitable for lumbosacral and sacral hemivertebral deformities, but it is less effective for thoracic deformities, especially thoracolumbar hemivertebral deformities, and further improvement of postoperative external fixation is needed.

Data availability statement

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

Ethics statement

This study was approved by the Ethics Committee of the Third Affiliated Hospital of Zhengzhou University.

Author contributions

The authors confirm contribution to the paper as follows: BX: contributed the conception and design of the study, reviewed, augmented the drafted manuscript. HQ and YM: performed literature review, synthesized data, prepared the draft of the final manuscript. FY: assisted with contributing data for the drafting of the manuscript and provided supervisory support. 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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Reliability and repeatability of a modified thoracolumbar spine injury classification scoring system

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Purpose: On the basis of the Thoracolumbar Injury Classification and Severity Score (TLICS), an modified TLICS classification system was presented, its reliability and repeatability were assessed, and the factors influencing classification consistency were examined.

Methods: Five spinal surgeons were chosen at random. The clinical data of 120 patients with thoracolumbar fractures admitted to the Department of Spine Surgery, Ningbo Sixth Hospital from December 2019 to June 2021 were categorized using the modified TLICS system. After 6 weeks, disrupt the order of data again. Using unweighted Cohen's kappa coefficients, the consistency of the modified TLICS system was assessed in five aspects: neurofunctional status, disc injury status, fracture morphology, posterior ligament complex (PLC) integrity, and treatment plan.

Results: In terms of reliability, the average kappa values for the subclasses of the modified TLICS system (neurofunctional status and disc injury status) were 0.920 and 0.815, respectively, reaching the category of complete confidence. Fracture morphology and treatment plan had average kappa values of 0.670 and 0.660, respectively, which were basically reliable. The average kappa value of PLC integrity was 0.453, which belonged to the category of moderate confidence. The average kappa coefficients of each subcategory (neurological status, disc injury status) had excellent consistency, and the kappa values were 0.936 and 0.879, respectively, which belonged to the completely credible category. The kappa values of fracture morphology and treatment plan repeatability were 0.772 and 0.749, respectively, reaching the basic credibility category. PLC integrity repeatability kappa value is low, 0.561, to moderate credibility category.

Conclusion: The modified TLICS system is intuitive and straightforward to understand. The examination of thoracolumbar fracture injuries is more exhaustive and precise, with excellent reliability and repeatability. The examination of neurological status and disc injury status is quite reliable and consistent. The consistency of fracture morphology is slightly poor, which is basically credible; the PLC integrity consistency is poor, reaching a reliability level of moderate, which may be associated with the subjectivity of clinical evaluation of PLC.

KEYWORDS

thoracolumbar fracture, severity, scoring, reliability and repeatability, modified typing

Background

Thoracolumbar fractures often refer to injuries of the T11-L2 segment, which is the most common type of spinal injury and is frequently caused by direct trauma, accounting for about 80% of spinal injuries (1). Due to the unique anatomical location and characteristics of the thoracolumbar segment, the clinical manifestations and treatment after injury differ from those of thoracic and lumbar fractures. If timely diagnosis and treatment are not obtained, or if the treatment method chosen is unreasonable, it is not conducive to improving the long-term quality of life of patients (2, 3). The classification of thoracolumbar fractures is important for clinical treatment and prognosis. At present, the Denis, AO, and TLICS system are the most prevalent staging approaches. However, the Denis classification is too basic to cover all fracture types and has limited clinical significance (4). The AO classification is quite complex, and its therapeutic application is difficult to learn. In the meantime, the average kappa value for confidence is 0.517, and the kappa values for each subtype are lower, placing them in the category of low to moderate confidence (5, 6). For the first time, the TLICS classification considers fracture morphology, PLC integrity, and neurofunctional status as key variables in assessing fracture damage severity and guiding physicians in selecting whether to pursue surgical intervention and how to select the surgical method. In recent years, numerous academics have evaluated the reliability and repeatability of the TLICS classification system, and research indicates that it may be the most reliable and effective classification system for the current clinical evaluation of the treatment of thoracolumbar fractures (7–9). Later, as MRI technology and spinal biomechanics progressed, researchers became increasingly worried about the influence of intervertebral disc and ligament structural integrity on the stability of the spine. Changes in spinal structure following a fracture can be categorized as bone structure changes or non-bone structure changes. Existing categorization approaches focus mostly on bone structure changes. Although the TLICS method considers PLC integrity, the impact of intervertebral disc damage on spinal stability was not examined. In addition, due to limits in technical progress and a multitude of influencing factors, PLC integrity cannot be assessed reliably, compromising the consistency of the TLICS system (10–12). Consequently, we presented a modified TLICS system, which included the evaluation of "disc injury status" and a reduction in the score for "PLC integrity." This study aims to recruit 120 patients with thoracolumbar fractures admitted to the Spinal Surgery Department of the Sixth Hospital of Ningbo City between December 2019 and June 2021 to examine the reliability and repeatability of the modified TLICS system, investigate the clinical guiding significance of the system, and investigate the factors affecting the system's consistency.

Materials and methods

General information

Patients have been diagnosed with fresh single-stage traumatic thoracolumbar fractures and no other serious injuries or illnesses. In addition, complete clinical imaging data and informed consent signed by patients and their families were also necessary. Thoracolumbar fractures that were multi-level or have been there for more than 3 weeks should be ruled out. Patients with osteoporotic fractures, severe multiple trauma, such as a head injury, and missing or incomplete imaging data should be excluded as well.

The study comprised a total of 120 patients with thoracolumbar fractures, including 68 males and 52 females. Imaging data included preoperative anteroposterior and lateral thoracolumbar x-ray, CT, and MRI. All data did not contain any information and markers related to the classification. The study was authorized by the Ethics Committee of Ningbo Sixth Hospital, and all procedures were conducted in accordance with applicable rules and standards. All patient-related information was authorized for publication by the patients or their legal guardians.

Research method

This study proposed a modified TLICS system to add the subcategory of "disc injury status" and lower the score of "PLC integrity" based on the clinical data collected, previous domestic and foreign literature publications, and the TLICS system. The subcategory of "disc injury status" should be analyzed in conjunction with MRI imaging data, classified into no injury, mild injury, and moderate-to-severe injury based on imaging characteristics of disc injury, and assigned 0, 1, and 2 points, respectively (**Figure 1**). The score assigned to the "PLC integrity" subcategory was appropriately reduced, with 0 points assigned when there was no injury to the PLC, 1 point assigned when there was a suspicious injury to the PLC, and 2 points assigned when there was an injury. The overall score of fracture morphology, PLC integrity, neurofunctional state, and disc damage status then guided clinical therapy and prognosis (**Table 1**). When the total score was $T < 4$, non-surgical treatment was administered; when the total score was $T = 4$, either non-operative or surgical treatment was administered; and when the total score was $T > 4$, surgery was performed (**Figures 2, 3**). Two associate chief physicians and three attending physicians were chosen at random and instructed using the modified TLICS system. After completing the training, five physicians categorized and rated the imaging data of five patients with thoracolumbar fractures to assess the mastery of the scoring system. After the

 10.3389/fsurg.2022.1054031

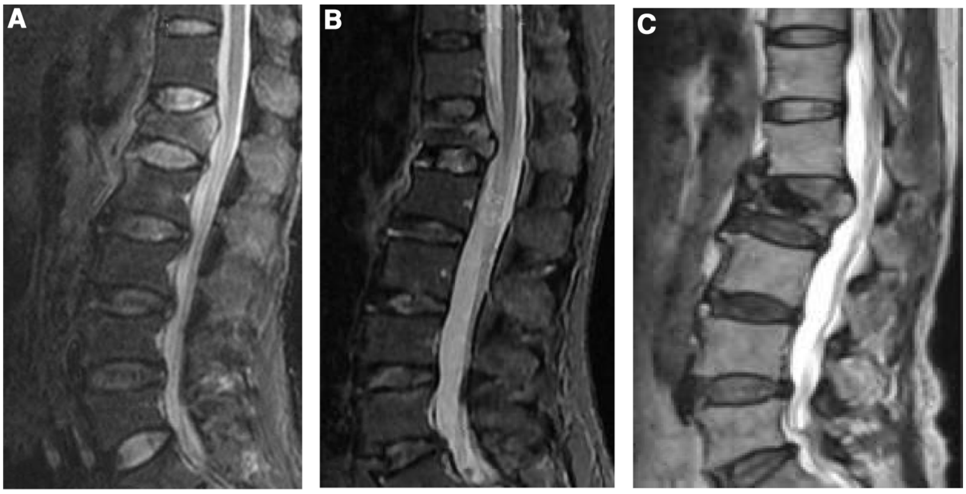

FIGURE 1
According to the imaging characteristics of disc injury, it was divided into three categories: no injury, mild injury, and moderate-to-severe injury (sagittal MRI images of the thoracolumbar segment before treatment). (A) No intervertebral disc injury (0 points). (B) Mild intervertebral disc injury, signal change, no endplate injury, with or without space change (1 point). (C) Moderate-to-severe intervertebral disc injury, significant signal change, end plate fracture, intervertebral disc contents herniated into vertebral body, intervertebral space change (2 points).

TABLE 1 Modified TLICS staging scoring system.

Subcategory/system score	TLICS System	Modified TLICS system
Fracture morphology		
Compressive	1	1
Bursting	2	2
Reduced force and rotational	3	3
Distraction	4	4
Neurofunctional status		
No injury	0	0
Nerve root injury	2	2
Complete spinal cord/Conus injury	2	2
Incomplete spinal cord/Conus injury	3	3
Cauda equina injury	4	4
PLC integrity		
No injury	0	0
Uncertain	2	1
Disruption	3	2
Disc injury status		
No damage		0
Mild injury		1
Moderate-to-severe injury		2

test was qualified, the medical image data of 120 patients were independently scored by 5 physicians and allowed to refer to the original literature. After 6 weeks, disrupted the order of data again classification score. The results of the two classifications were recorded by physicians who were not involved in the classification, and the correlation between the final total score T and the choice of treatment plan was analyzed. Then the reliability and repeatability of the modified TLICS system were analyzed to explore the reasons for the consistency of the classification. For the same patient, 5 physicians in classification were inconsistent as long as there was a physician classification of any sub-category score that was different.

Observation items and methods

At first, a correlation study was performed to clarify the relationship between the scores of the modified TLICS system and the patient's final treatment plans. The consistency of the modified TLICS system was then assessed. The observation indicators included the scores of each subtype supplied by the modified TLICS system at two stages before and after five physicians, and the scores of each subtype among five physicians were statistically added at two stages before and after five physicians. According to the reliability evaluation criteria of Landis and Koch, the reliability was analyzed by the consistency kappa test, and the repeatability of two-stage categorization scores before and after the same doctor was studied.

Statistical processing

The correlation between modified TLICS system scores and patient treatment regimens was analyzed by Pearson correlation analysis with a test level of $\alpha = 0.05$, and $P < 0.05$ indicates that

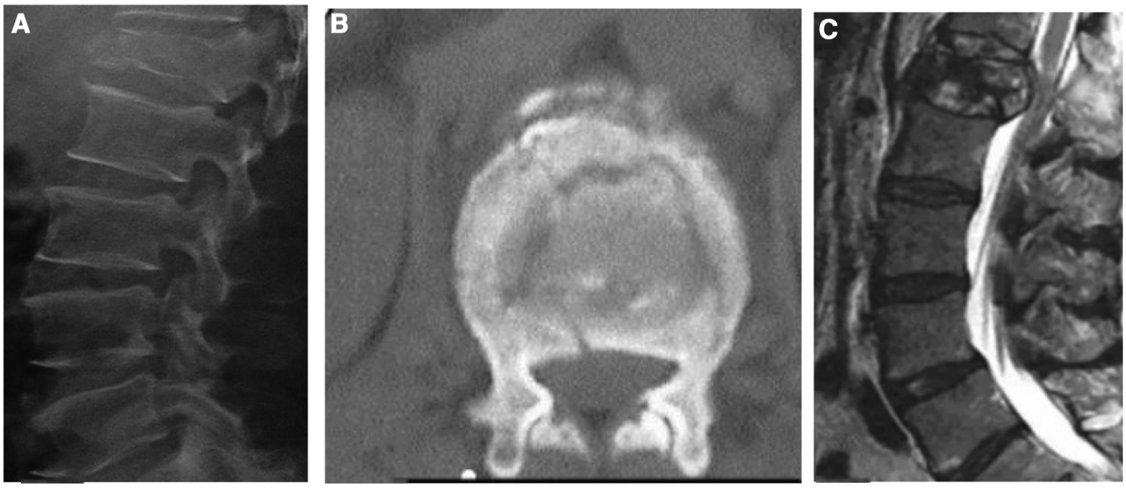

FIGURE 2
Patient, a male, 52 years old, was hospitalized for 1 day with low back pain due to trauma, no neurological symptoms, and was diagnosed with an L1 burst fracture. (A,B) burst fracture of L1 vertebral body, no neurological injury; (C) L1 burst fracture, no neurological injury, suspicious injury of PLC status, severe disc injury status. **The modified TLICS system:** burst fracture (2 points), suspicious PLC injury (1 point), severe disc injury status (2 points), no neurological injury (0 points), T = 5 points, surgical treatment is recommended. **The TLICS system:** T = 4 points; treatment choices are recommended according to the patient's specific situation, and there are differences between them.

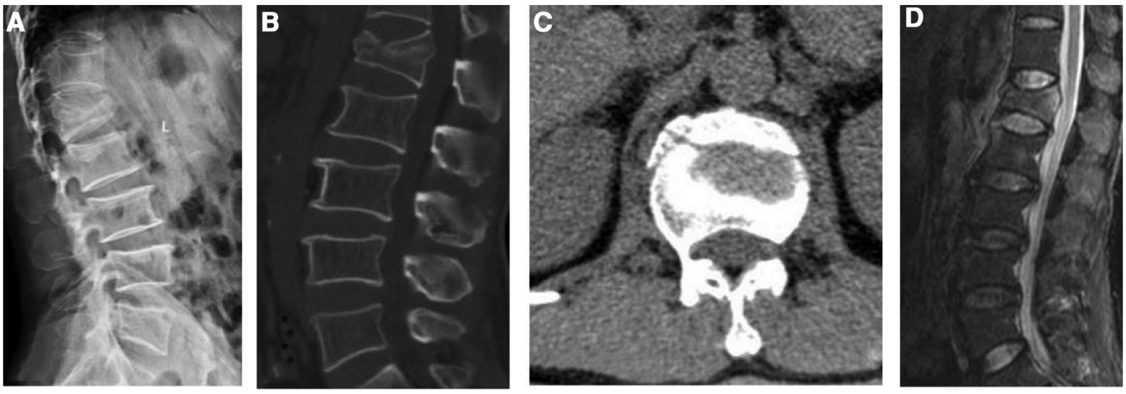

FIGURE 3
Patient, a male, 44 years old, was hospitalized for 2d for traumatic back pain, no neurological symptoms, diagnosed as L1 burst fracture. (A–C) suggesting an L1 burst fracture with no nerve damage; (D) an L1 burst fracture with no damage to the PLC, no damage to the intervertebral disc, and no neurological injury. **The modified TLICS system:** burst fracture (2 points), no damage to the PLC (0 points), no damage to the intervertebral disc (0 points), no neurological injury (0 points), T = 2 points, Non-surgical treatment is recommended based on the modified TLICS system.

the difference is statistically significant. An inter-observer consistency test (reliability analysis) was conducted for intra-group typing data, an intra-observer consistency test (repeatability analysis) was performed on the inter-group typing data, and SPSS 26.0 software was used to calculate the kappa coefficient. The degree of consistency was judged according to the Landis and Koch (11) classification system. When Kappa value >0, it is meaningful. The greater the Kappa coefficient, the better the reliability or repeatability. When the Kappa value is 0.00–0.20, it indicates poor consistency and belongs to the category of mild credibility; when the Kappa value is 0.21–0.40, it indicates general consistency and belongs to the category of mild to moderate credibility; When the Kappa value is 0.41–0.60, it indicates moderate consistency and belongs to moderate credibility category; When the Kappa value is 0.61–0.80, it shows good consistency and belongs to the basic credible category; when the Kappa value is 0.81–1.00, it shows excellent consistency and is completely credible.

Results

A total of 120 patients with thoracolumbar fractures were included in this study, comprising 68 men and 52 females, and aged 22~65 (36.7 ± 5.7) years old. The demographic information is displayed in **Table 2**. Among the 120 patients, based on the scores obtained from the modified TLICS system, combined with the systemic conditions and personal wishes, 38 patients had a total score of T < 4, of which 30 were treated conservatively and 8 surgically; 17 patients had a total score of T = 4, of which 5 were treated conservatively and 12 surgically, and 65 patients had a total score of T > 4, of which 4 were treated conservatively and 61 surgically. A correlation analysis of the patients' modified TLICS system score T with the treatment plan revealed a Pearson correlation coefficient of 0.688 and a strong correlation between the two (**Table 3**).

Five physicians graded 1,200 times 120 individuals with thoracolumbar fractures(120 cases*5 individuals*2 times). The modified TLICS system's reliability kappa coefficients for each subclass (neurofunctional status and disc injury status) demonstrated excellent consistency across the two classifications, with neurofunctional status having kappa values of 0.903 and 0.936 and disc injury status having kappa values of 0.842 and 0.788, both of which fell into the category of being completely credible. The fracture morphology reliability ratings were 0.660 and 0.698, and the treatment plan reliability scores were 0.625 and 0.694; both scores fell into the basic reliability category. The kappa value of PLC integrity reliability was somewhat low (0.417 and 0.488, respectively), placing it in the moderate reliability category. The repeatability kappa value of each subcategory (neurofunctional status and disc injury status) demonstrated excellent consistency, with kappa values of 0.936 and 0.879, respectively, belonging to the category of being completely credible. The repeatability kappa values for fracture morphology and treatment plan were 0.77 and 0.74, respectively, placing them in the basic credible category. The repeatability kappa value for PLC integrity was low, 0.561, placing it in the moderate credibility category (**Tables 4**, **5**).

TABLE 2 General information of patients.

General Information	Number of people (cases)
Sex	
Male	68
Female	52
Age	36.7 ± 5.7
Fracture segment	
T11	14
T12	45
L1	54
L2	27
ASIA Grading	
A	3
B	8
C	12
D	28
E	69
Cause of injury	
Traffic Accidents	63
Crushing by weight	27
Falling from height	18
Other reasons	12

TABLE 3 Correlation of modified TLICS system scores with the treatment plan.

		Total Score	Treatment plan
Total Score	Pearson Correlation	1	0.688
	Sig. (bobtail)		0.000
	Number of cases	120	120
Treatment plan	Pearson Correlation	0.688	1
	Sig. (bobtail)	0.000	
	Number of cases	120	120

Discussion

Necessity and theoretical basis for the proposed modified TLICS system

The thoracolumbar segment of the spine (T11-L2) is a structural transition zone from the thoracic to the lumbar spine, with the articular facets gradually shifting from the coronal to the sagittal plane and a dramatic increase in spinal mobility; its unique anatomical structure and stress mechanism are intrinsic factors in the high incidence of spinal injuries in the thoracolumbar segment. Thoracolumbar fractures are frequently accompanied with spinal nerve damage, which has a high rate of disability and negatively impacts patients' daily lives and quality of life. Consequently, its therapeutic care is very crucial (12-14). The treatment plan for thoracolumbar fractures is primarily determined by assessing spinal stability, and non-operative treatment is typically selected for stable thoracolumbar segment fractures; surgical treatment is selected for unstable fractures to prevent the deterioration of neurological function and the development of secondary symptomatic spinal deformities (15–17). But, the academic community lacks a unified standard for measuring spinal stability, and the thoracolumbar fracture classification system currently in use has significant problems. For example, the Denis classification system is overly simplistic, and its method for distinguishing between

10.3389/fsurg.2022.1054031

TABLE 4 Comparison of reliability and repeatability of kappa values for each subtype and treatment of modified TLICS system by five physicians.

Physicians	Fracture morphology		Neurofunctional status		PLC integrity		Disc injury status		Treatment plan	
	Rel	Rep	Rel	Rep	Rel	Rep	Rel	Rep	Rel	Rep
1	0.663	0.782	0.915	0.927	0.418	0.548	0.819	0.891	0.656	0.745
2	0.608	0.728	0.927	0.921	0.397	0.478	0.767	0.831	0.564	0.691
3	0.716	0.788	0.901	0.948	0.477	0.586	0.782	0.855	0.644	0.777
4	0.697	0.765	0.930	0.948	0.513	0.612	0.864	0.927	0.727	0.805
5	0.711	0.797	0.927	0.936	0.460	0.581	0.843	0.891	0.709	0.727

Rel, Reliability; Rep, Repeatability.

TABLE 5 Reliability and repeatability of each subtype of the modified TLICS system.

Subcategory		The first time	The second time	Kappa value
Fracture morphology	Rel	0.660	0.698	0.679
	Rep	—	—	0.772
Neurofunctional status	Rel	0.903	0.936	0.920
	Rep	—	—	0.936
PLC integrity	Rel	0.417	0.488	0.453
	Rep	—	—	0.561
Disc injury status	Rel	0.842	0.788	0.815
	Rep	—	—	0.879
Treatment plan	Rel	0.625	0.694	0.660
	Rep	—	—	0.749

Rel, Reliability; Rep, Repeatability.

stable and unstable fractures is suspect and unreliable. The AO classification system consists of 53 subcategories that are complicated, difficult to remember, and limited in their repeatability. According to research on reliability, the reliability of AO between main kinds is about 67%, and it is considerably lower within subtypes, which have limited clinical practice guiding significance. In addition, the classification lacks a defined definition of “stability” and excludes neurofunctional status as a criterion of scoring (18). The TLICS classification system is a frequently utilized thoracolumbar fracture scoring system; nevertheless, various spinal surgeons may have varying opinions regarding the integrity of the PLC, and the influence of intervertebral disc damage on spinal stability is not taken into account. Therefore, there is a need for a simple and practicable scoring system that considers the immediate stability, long-term stability, and nerve stability of the spine in order to effectively identify the degree of fracture injury, direct therapeutic therapy, and predict prognosis.

Characteristics of the modified TLICS system

The features of our proposed modified TLICS type system are as follows: (1) In recognition of the scientific character of the TLICS type system, the subcategories “fracture morphology” and “neurofunctional status” were retained to signify, respectively, the immediate stability and neurological stability following spinal fractures. (2) Although the TLICS system takes into account the effect of PLC integrity on the long-term stability of the spine, it is sometimes difficult to assess the PLC’s integrity properly in clinical practice. It frequently necessitates the subjective evaluation of patient symptoms and clinical experience by physicians. In this study, the reliability and repeatability kappa values of the “PLC integrity” subcategory were 0.453 and 0.561, respectively, which only reached the moderate confidence category. At the same time, the PLC only bears a large tension load when the spine is subjected to flexion deformity stress, and the anterior and middle spinal structures are more important in maintaining the axial forces in the spine, which bear 70%–80% of the axial compressive stress in the spine and are the most important anatomical structures for maintaining spinal stability. Spinal kyphosis and mechanical instability are mostly due to a lack of support in the anterior and middle columns rather than insufficient posterior column support strength. Therefore, assessing PLC integrity separately from vertebral bony structural damage may lead to an overemphasis on the role of the posterior column (19–21). Therefore, the TLICS system was changed so that "PLC integrity" got a lower score to make it more reasonable. Therefore, the modified TLICS system reduced the score assigned to "PLC integrity" to make it more reasonable. (3) The modified TLICS system classified "disc injury status" as no injury, mild injury, and moderate-to-severe injury. This was the first time that disc injury status was included in the system. This was reasonable because it focused more on how stable the spine will be in the long run.

Analysis of the reliability and repeatability of the modified TLICS system

The result of this study demonstrated that the modified TLICS system's subcategories for neurofunctional status and disc injury status had excellent consistency. The average kappa values of the subcategories of fracture morphology and treatment plan could reach the basic credible category, while the average kappa value of PLC integrity could only reach the category of moderate confidence. Combining the results of a previous multicenter TLICS system consistency study (22) (fracture morphology, neurofunctional status, PLC integrity, and treatment plan, with average kappa values of 0.430, 0.850, 0.470, and 0.290 for reliability and 0.590, 0.900, 0.550, and 0.440 for repeatability, respectively), we found that both systems had comparable consistency in the neurofunctional status and PLC integrity subcategories, reaching the full and moderate levels of agreement, respectively. When it came to fracture morphology and treatment plan subcategories, the modified TLICS system had better consistency than the TLICS system. Therefore, we had grounds to infer that the modified TLICS system had better consistency than the TLICS system and was more favorable to the clinical diagnosis and treatment of thoracolumbar fractures. Due to the absence of a direct comparison between the two categorization systems in this study, there were several unpredictable variables, including physicians' varying mastery of the classification system and patients' varying acceptance of surgical therapy. To compare the consistency of the two kinds, further controlled research is required.

Exploration of factors affecting the consistency of the modified TLICS system

Reducing the influence of the "PLC status" subcategory assignment

The modified TLICS system assessed each subcategory of fracture morphology, neurofunctional status, disc injury status, and PLC integrity independently, and the cumulative total score determined the treatment plan. From the two classifications, it was evident that the consistency of PLC integrity subcategories was low, and the kappa values of reliability and repeatability were 0.453 and 0.561, respectively, which had a significant impact on the final choice of treatment plan, which may be associated with the accurate assessment of PLC injury status and unreasonable assignment. The PLC consists of the supraspinous ligament, the interspinous ligament, the ligamentum flavum, and the facet joint capsule. It is responsible for the everyday biomechanical actions of the spine, together with the anterior and middle columns, in order to preserve spine stability. Physical examination, x-rays, computed tomography(CT), magnetic resonance imaging (MRI), etc, are currently the most used clinical procedures for determining the extent of PLC damage. When a patient is obese, for instance, the diagnosis may be missed due to an inability to reach the spinous process; when there is bleeding in the spinal canal, it is easy to produce the appearance of a ligamentum flavum injury. Many studies reported similar issues, Zhang Yang et al. (23) discovered that the sensitivity, specificity, and accuracy of physical signs to examine PLC injury were low, with large differences between intraoperative exploration results. Hartmann et al. (24) discovered that examining PLC injury with x-ray and CT bony parameters had low sensitivity and specificity. Rihn et al. (25) considered the presence of a high signal in MRI lipid suppression images as the basis of PLC injury, but the specificity of this method is only 68.4%, making accurate judgment difficult. When none of the techniques can precisely assess the condition of a PLC injury, physicians must depend on their subjective clinical experience. Concurrently, PLC questionable damage was awarded 2 points, and damage was assigned 3 points, which immediately contributed to a substantial rise in the overall score T. PLC as part of the morphological structure of the spine, in theory, should be evaluated as a whole morphology, and separate score should not be offered. Consequently, assessing PLC damage and bone structural damage separately may result in an overemphasis on the function of PLC and repetitive scoring (26).

Addition of the "disc injury status" subcategory

Compared to the TLICS system, the modified TLICS system added the subcategory "intervertebral disc injury". The reliability and repeatability kappa values were 0.815 and 0.879, respectively, which were both completely credible. According to studies (27), when direct violence is applied to the human body quickly, intervertebral disc injury is often unavoidable, and the upper intervertebral disc of the injured vertebra is more likely to be injured than the lower intervertebral disc. And the vertebral body itself accounts for only 38% of the unstable factors after thoracolumbar fractures, while the remainder is attributed to the intervertebral disc structure. When the disc injury is mild, the disc tissue does not herniate into the injured vertebral body, and conventional posterior surgery can successfully restore the normal height of the injured vertebrae, correcting the posterior convexity deformity, and restoring the intervertebral space height by bracing and resetting, allowing the damaged disc tissue to heal. When the intervertebral disc tissue is severely damaged, some of the disc tissue herniates into the injured vertebral body, the osteogenic ability is reduced, the bone healing ability is poor, and there is a possibility of instability and recompression. Coupled with the limited self-repair function of the disc tissue, the patient has a higher possibility of delayed retroconvex deformity (28–30). As a result, it is simple to conclude that spinal stability and intervertebral discs are related. According to the imaging characteristics of intervertebral disc injury, the modified TLICS system combined with MRI imaging data was therefore analyzed and classified into no injury, mild injury, and moderate-to-severe injury, and assigned 0, 1, and 2 scores, respectively. These scores, when combined with the other three subcategories, could aid in determining the severity of the fracture and providing clinical treatment.

Conclusion

In conclusion, the modified TLICS system is intuitive and easy to use. When compared to the TLICS system, the modified TLICS system lowered the PLC integrity score and made treatment plan selection more objective. The addition of disc injury status subcategories, focusing more on the long-term stability of the spine, will assist clinicians in treating thoracolumbar fractures clinically and determining prognosis. Nonetheless, this is a retrospective, single-center study with a limited sample size. Moreover, given the limited size of our hospital, the lack of sample size calculation in this study weakens the trustworthiness of our findings. Therefore, with a larger sample size and perspective, multicenter research to confirm its clinical usefulness is required to conduct a more scientific evaluation and improve this method system.

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.

Author contributions

W-jL Writing - Original Draft, Data Curation. Y-gD Resources. JZ Formal analysis. WJ Conceptualization, Methodology, Supervision. 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.

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Case report: Thoracolumbar spinal stenosis associated with alkaptonuria

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Background: Alkaptonuria is a rare autosomal genetic disorder with an incidence of about 1 in 1 million per year. Spinal involvement often manifests in the later stages of the disease. However, this is the first report of the presentation of thoracolumbar spinal stenosis.

Case presentation: We report the case of a 61-year-old female patient with significant thoracolumbar stenosis symptoms. The patient had obvious kyphosis with preoperative lower extremity muscle strength grade 2/5. Symptoms and imaging signs initially suggested ankylosing spondylitis. This patient was classified into motor incomplete injury (ASIA C). However, the patient was found to have melanin deposits on the sclera and skin, and the urine was darkened at rest. CT and MRI both suggested no bone bridge connection between vertebrae, which was the key difference between ankylosing spondylitis and alkaptonuria in imaging. Most importantly, urine specimen testing and intraoperative pathology demonstrated alkaptonuria. The patient underwent spinal decompression and vertebral body fixation. Postoperative recovery was good: the patient had significantly relieved pain and could stand and walk.

Conclusion: This case is the first report of thoracolumbar spinal stenosis associated with alkaptonuria involving the spine.

KEYWORDS

alkaptonuria, thoracolumbar spinal stenosis, case report, surgery, kyphosis

Introduction

Alkaptonuria (AKU) is a rare genetic disease with an incidence of about 1 in 1 million per year (1). The early manifestation of AKU involves the darkening of urine after resting. The progression appears as melanosis of the skin and sclera. In the late stages of disease progression, homogeneous acid (HGA) deposits in tissues such as cartilage, tendons, and ligaments lead to the degeneration of the spine and large peripheral joints. Spinal canal stenosis frequently occurs in the cervical and lumbar spine but rarely in the thoracolumbar segment (2).

We describe here for the first time the case of a 61-year-old patient with AKU presenting with thoracolumbar spinal stenosis.

Case report

A 61-year-old female patient complained of recurrent low back pain for more than 10 years and pain and numbness in both legs for approximately 8 months. We found that the patient's parents are married cousins, suggesting that the patient may have a genetic disorder. Physical examination revealed that the patient had significant kyphosis. Melanosis could be seen in both sclerae and both auricles. There were hypoesthesia and hypoalgesia below the T10 dermatome. The muscle strength for hip flexion, knee extension, and knee flexion was grade 3/5, while ankle dorsal extension and metatarsal flexion were grade 2/5. The patient exhibited hyperreflexia of both Achilles tendons and knees; furthermore, Babinski's sign, Gordon's sign, Oppenheim's sign, and the four-figure test were positive on both sides. This patient was classified into motor incomplete injury (ASIA C). On imaging examination, plain lumbar spine radiographs demonstrated that all the lumbar disc spaces were narrow with signs of osteoporosis. Magnetic resonance imaging (MRI) revealed spinal stenoses of the T10/11, L1/2, and L2/3 segments. Laboratory examination depicted that the fresh urine was light yellow and gradually turned dark brown after a period of time. Pathological examination revealed melanin deposits in the intervertebral disc and ligament tissues.

The patient underwent adequate intraoperative spinal canal decompression and was fixed with pedicle screws. At operation, we found that the bone junctions of the supraspinous ligament, interspinous ligament, and ligamentum flavum were blackened. Severe T10/11 disc degeneration was noted, with no significant distinction between the nucleus pulposus and the adjacent tissue.

The patient experienced remarkable relief and was discharged 1 week after the operation. The patient's muscle strength returned to grade 4/5 after surgery, and she could stand and walk independently. A review is scheduled for 3 months after surgery and lumbosacral surgery at an optional date, depending on the patient's condition.

Discussion

This was the first description of alkaptonuria presenting as thoracic spinal stenosis. AKU is an autosomal recessive hereditary disease with an incidence of about 1 in 1 million per year (1, 3). This patient presented with symptoms similar to those of ankylosing spondylitis (AS) and was eventually diagnosed as an extremely rare case of alkaptonuria, which resulted in good recovery through surgery, so we feel it is important to report this case. The early clinical manifestations of AKU are mainly dark urine or deepening of urine color and hyperpigmentation, mostly in the sclera and external auricle. As the disease progresses, the deposits lead to stiffness of the connecting tissues, premature degeneration of the spinal joints, and labral osteophytes at the edges of the vertebral column (4). The characteristic imaging features include extensive intervertebral space narrowing and pancake-like disc calcification, sometimes with disc vacuum (5, 6).

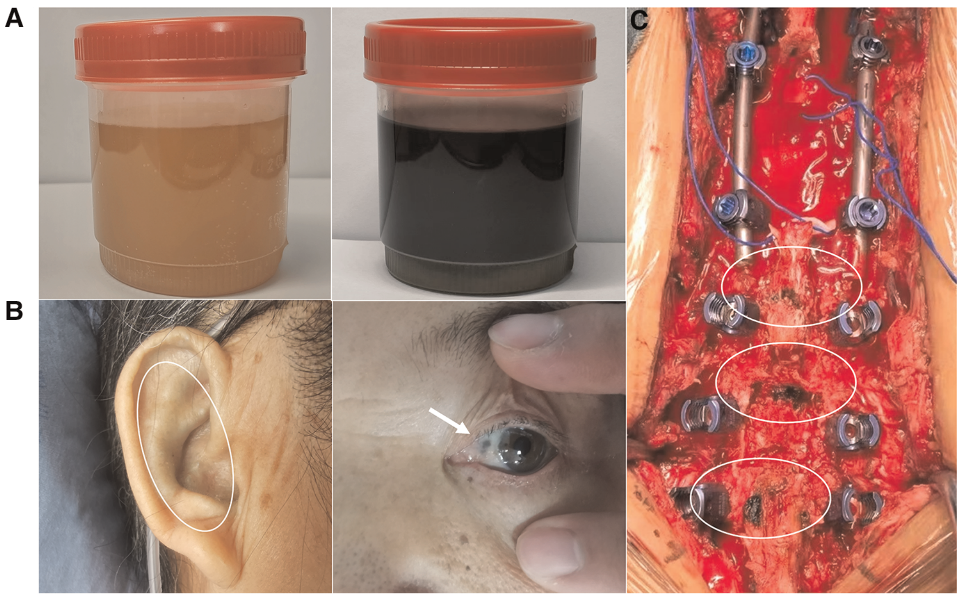

FIGURE 1
Patient's urine darkened after resting (A); melanin deposition in the sclera and external auricle (B); intraoperatively, the bony junction of the interspinous ligament, supraspinous ligament, and ligamentum flavum were black (C).

In the currently reported patient, melanin deposition in the sclera and external auricle and darkening of the urine after resting were observed. In the operation, the T10/11 disc was found to be severely degenerated, and the nucleus pulposus was indistinguishable from the adjacent tissue. Intraoperatively, parts of the interspinous ligament, supraspinous ligament, and ligamentum flavum were found to be darkened (**Figure 1**). Disc herniation has been previously reported in patients with AKU (7, 8), but severe thoracolumbar spinal canal stenosis is rare (9). Alkaptonuria patients are easily misdiagnosed as AS. AS can be followed by disc fibrosis and calcification, bony ankylosis of the spine, and the characteristic bamboo spine (10). Increased brittleness of spinal bone due to bony ankylosis of the spine and vertebral osteoporosis in late AS, combined with a stress increase in the thoracolumbar segment, leads to a fracture called an Andersson lesion (11). However, imaging data revealed that the patient had multiple intervertebral degenerations, including decreased intervertebral height, destruction of the upper and lower endplates, and low signal in the nucleus pulposus region on T2 images owing to atrophy and dehydration of the nucleus pulposus. No significant vertebral fusion was found in the spine (**Figure 2**). This is the point of differentiation from the presentation of patients with AS.

Narrowing of the spinal canal or foramina is a common finding in spine imaging of the elderly. Only when symptoms of neurogenic claudication and/or cervical myelopathy are present is a spinal stenosis diagnosis made, of the lumbar spine, cervical spine, or both (only very rarely is the thoracic spine involved) (2). The patient in the case report had significant preoperative spinal cord symptoms, was unable to walk independently, was pushed in a wheelchair, and had

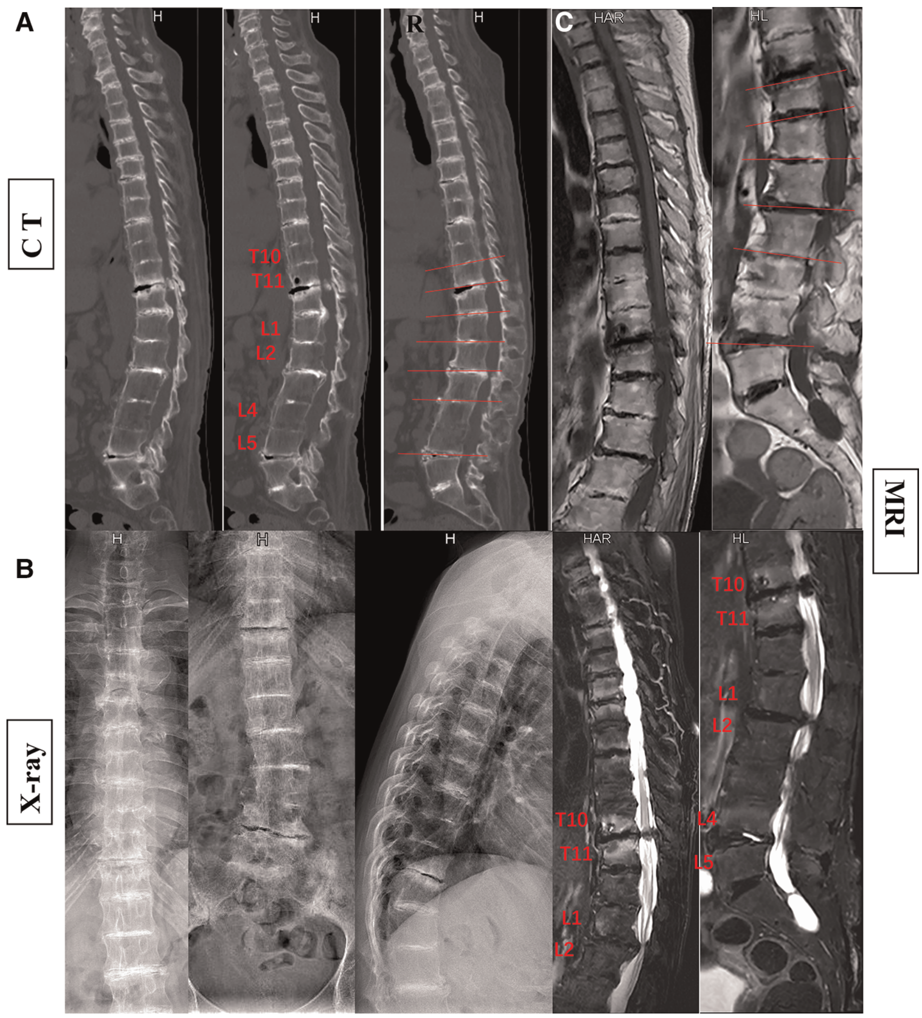

FIGURE 2
The patient's preoperative imaging examination revealed kyphosis and spinal stenosis. Disruption and stenosis of the intervertebral disc with labral changes. Intervertebral ossification dysplasia, vertebral body without ossification connected (**A**, CT; **B**, x-ray; **C**, MRI).

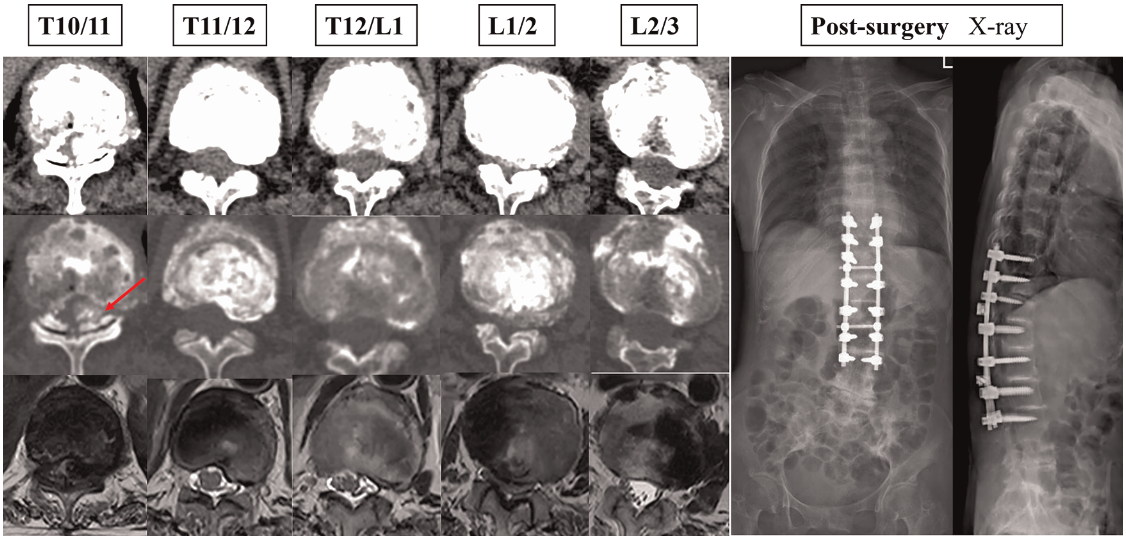

FIGURE 3
The patient's preoperative cross-sectional imaging examination and postoperative x-ray maps.

preoperative muscle strength of grade 2/5. Postoperatively, she could stand and walk, and her muscle strength returned to grade 4/5. Thoracic spinal stenosis is a rare entity for which the incidence is unknown (12). Spinal stenosis can be classified etiologically into two categories: congenital and acquired (13). Most patients will have acquired canal stenosis, often due to degenerative causes, systemic illness or postsurgical pathology (2). This patient has significant thoracolumbar stenosis. Intraoperatively, we found darkening of the ligamentum flavum with significant melanin deposition, which suggests that the cause of T10/11 segment stenosis is mainly the calcification of the ligamentum flavum (**Figure 3**). The reason for ossification of the ligamentum flavum may be the deposition of HGA. Additionally, disc degeneration and loss of height may force invagination of the ligamentum flavum and subsequent pressure on the dural dorsal capsule, contributing to hypertrophy of the ligamentum flavum (2).

Currently, there is no effective therapy for AKU, and symptomatic supportive treatment is the mainstay. Dietary restrictions on phenylalanine and tyrosine intake and oral vitamin C are suggested to reduce the production and deposition of HGA (14–16). It has been reported that nitisinone can reduce HGA production and has a therapeutic effect on AKU (17, 18). Surgery is considered feasible for patients with spinal or peripheral large joint involvement to improve the quality of survival (19, 20).

Finally, this case report is a further reminder that orthopedic surgeons must be thorough in their examination and diagnosis and not abandon any suspected diagnoses. Surgery remains an important treatment for this condition.

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 Ethics Committee on Biomedical Research, West China Hospital of Sichuan University. 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

L-ML conceived, designed, and planned the study. HD wrote the manuscript. LW collected patient data. G-JF and Y-MS modified 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 in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Efficacy of a novel percutaneous pedicle screw fixation and vertebral reconstruction versus the traditional open pedicle screw fixation in the treatment of single-level thoracolumbar fracture without neurologic deficit

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Objective: The aim of this study was to compare the efficacy and safety of a novel percutaneous pedicle screw fixation and vertebral reconstruction (PPSR) vs. that of open pedicle screw fixation (OPSF) in the treatment of thoracolumbar fractures.
Methods: This retrospective study enrolled 153 patients who underwent PPSR and 176 patients who received OPSF. Periprocedural characteristics, radiographic parameters, and clinical outcomes were compared between the two groups.
Results: The operation duration was 93.843 ± 20.611 in PPSR group and 109.432 ± 11.903 in OPSF group; blood loss was 131.118 ± 23.673 in PPSR group and 442.163 ± 149.701 in OPSF group, incision length was 7.280 ± 1.289 in PPSR group and 14.527 ± 2.893 in OPSF group, postoperative stay was 8.732 ± 1.864 in PPSR group and 15.102 ± 2.117 in OPSF group, and total hospitalization costs were 59027.196 ± 8687.447 in PPSR group and 73144.432 ± 11747.567 in OPSF group. These results indicated that these parameters were significantly lower in PPSR compared with those in OPSF group. No significant difference was observed in the incidence of complications between the two groups. The radiographic parameters including height of the anterior vertebra, Cobb angle, and vertebral wedge angle were better in PPSR group than in OPSF group. Recovery rate of AVH was 0.449 ± 0.079 in PPSR group and 0.279 ± 0.088 in OPSF group. Analysis of clinical results revealed that during postoperative period, the VAS and ODI scores in PPSR group were lower than those in OPSF group.
Conclusions: Collectively, these results indicated that PPSR more effectively restored the height of anterior vertebra and alleviated local kyphosis

compared with OPSF. Moreover, the VAS and ODI scores in PPSR group were better than those of OPSF group.

KEYWORDS

thoracolumbar fracture, percutaneous pedicle screw fixation and vertebral reconstruction, anterior vertebral height, open pedicle screw fixation, vertebral reconstruction

Introduction

Spine injuries, especially thoracolumbar fractures caused by various factors such as accidents are on the rise. Thoracolumbar fractures account for more than 50% of all spinal fractures (1), and pose a huge economic burden to the society and families. Patients with stable spine fractures can be treated conservatively, while surgery is needed for severe damage of the vertebral column, kyphotic deformity, or neurological disorders (2). At present, operative indications of type A thoracolumbar fracture without neurologic deficit include: (1) kyphotic deformity > 15–20° (compared with normal angle); (2) the loss of vertebral body height > 50%. The objective of surgery for type A thoracolumbar fracture is to restore the vertebral body height, correct the Cobb angle, and correct the kyphotic deformity. Although the open pedicle screw fixation (OPSF) system is one of the most effective methods for treating thoracolumbar fractures, it suffers from several limitations. These include the difficulty in accurate placement of the screws and the necessity to obtain a wide exposure of the facets and transverse processes through dissection of the paravertebral muscles, which play a pivotal role in maintaining spinal stability. The traditional OPSF often causes excessive blood loss, requires prolonged hospital stays, and is expensive (3). In addition, vertebral fracture reduction under the conventional OPSF is not satisfactory because the anterior vertebral height (AVH) is restored and the Cobb angle corrected through longitude traction of the titanium rod. These disadvantages have limited the widespread use of OPSF in treating thoracolumbar fractures.

Magerl developed and reported for the first time in 1982 a minimally invasive percutaneous pedicle screw technique combined with external fixation (4). This technique minimized surgical trauma and decreased the surgical duration of spine surgery. In comparison to OPSF, the percutaneous pedicle screw technique has the advantages of less bleeding, shorter operative time, and lower visual analog scale (VAS) score after surgery (5). However, neither OPSF nor the traditional percutaneous pedicle screw fixation can restore the normal levels of postoperative AVH and the Cobb angle. It has been reported that the postoperative AVH and the correction of Cobb angle are gradually lost with time, in patients who receive the OPSF or the traditional percutaneous pedicle screw fixation (5–7) due to failure of reconstruction of the anterior column. According to the three-column spinal theory, a stable anterior spinal column is essential for normal spinal biomechanics (8). Although the traditional pedicle screw fixation technique can restore the stability of the posterior columns of the injured vertebra, it fails to restore the anterior spinal column. Consequently, the resulting biomechanical instability is often associated with low back pain and requires revision surgery. Therefore, it is crucial to develop a novel percutaneous pedicle screw fixation technique that is capable of reconstructing the anterior column.

Based on traditional percutaneous pedicle screw fixation, we devised a new technique named percutaneous pedicle screw fixation and vertebral reconstruction (PPSR). This technique can be used in the reconstruction of the anterior column by distracting the involved vertebra and providing bone grafting to promote vertebral healing. PPSR was used for treating patients who had vertebral compression fracture. This retrospective study was carried out to compare the efficacy of PPSR and the traditional OPSF. In this study, medical records of patients with thoracolumbar fractures were retrospectively reviewed. Clinical features and surgical outcomes of the two types of surgeries were compared. The results indicated that OPSF and PPSR give both short-term and long-term benefits. Other advantages include shorter operating time, reduced financial burden, and preservation of anterior vertebral height and the local vertebral Cobb angle. Therefore, the novel PPSR is a reliable method for treating thoracolumbar fractures and offers many benefits to patients.

Materials and methods

Patients

This was a retrospective cohort study that was approved by the Ethics Committee of the Wujin Hospital of Traditional Chinese Medicine (KY-S-2019002). This study has been revised according to the STROBE checklist which is provided in the supplemental file (**Supplementary File 1**). A total of 656 patients with thoracolumbar fracture treated from July 2018 to June 2022 were enrolled. Inclusion criteria were as follows: (1) thoracolumbar fractures (T10–L2) caused by trauma, confirmed by imaging; (2) single-segment vertebral fracture; (3) AO type A fracture; (4) the fracture occurred within one week prior to surgery; (5) no prior history of spinal fracture; (6) no spinal canal occupation; (7) had under gone PPSR or OPSF; (8) with complete case records. Exclusion criteria: (1) severe osteoporosis; (2) neurological deficit; (3) ankylosing spondylitis or spine malformation; (4) primary or secondary tumor of the spine. Thoracolumbar fracture was

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diagnosed using x-ray, computed tomography (CT) and magnetic resonance imaging (MRI). All surgical procedures were performed by the same senior spine surgeon. Data related to clinical follow-up were collected through either outpatient follow-ups or telephone contacts. Specifically, most type A1 patients who strongly demanded PPSR or OPSF were included in this study. Type A2 or A3 patients with vertebral compression fracture who accepted PPSR or OPSF were also included in this study. Eventually, 329 patients were enrolled in this study. Vertebral reconstruction in 153 patients was carried out using PPSR, while 176 patients underwent OPSF. All the patients were informed of the surgical treatment procedures as well as the benefits and risks of the surgeries. Upon admission, all the patients consented to the use of their data for scientific research. The procedures were performed by the same surgical team.

Operative procedures

The procedures for PPSR are presented in **Figure 1**. The PPSR procedure was as follows. (1) Preoperative positioning was first performed. Patients were placed in prone position with their shoulder and pelvis slightly raised after sedation with general anesthesia. Appropriate incisions for inserting percutaneous pedicle screw placement was confirmed by C-arm fluoroscopy. The pedicle positions of the fractured vertebra and the adjacent vertebrae were marked on the body surface. (2) Routine disinfection was carried out and sterile drapes were applied. Four longitudinal skin incisions (1.5–2 cm) were made at 1 cm lateral to the projection area of the adjacent vertebrae pedicles. Guide pins were inserted into the vertebra through the pedicles using C-arm fluoroscopy.

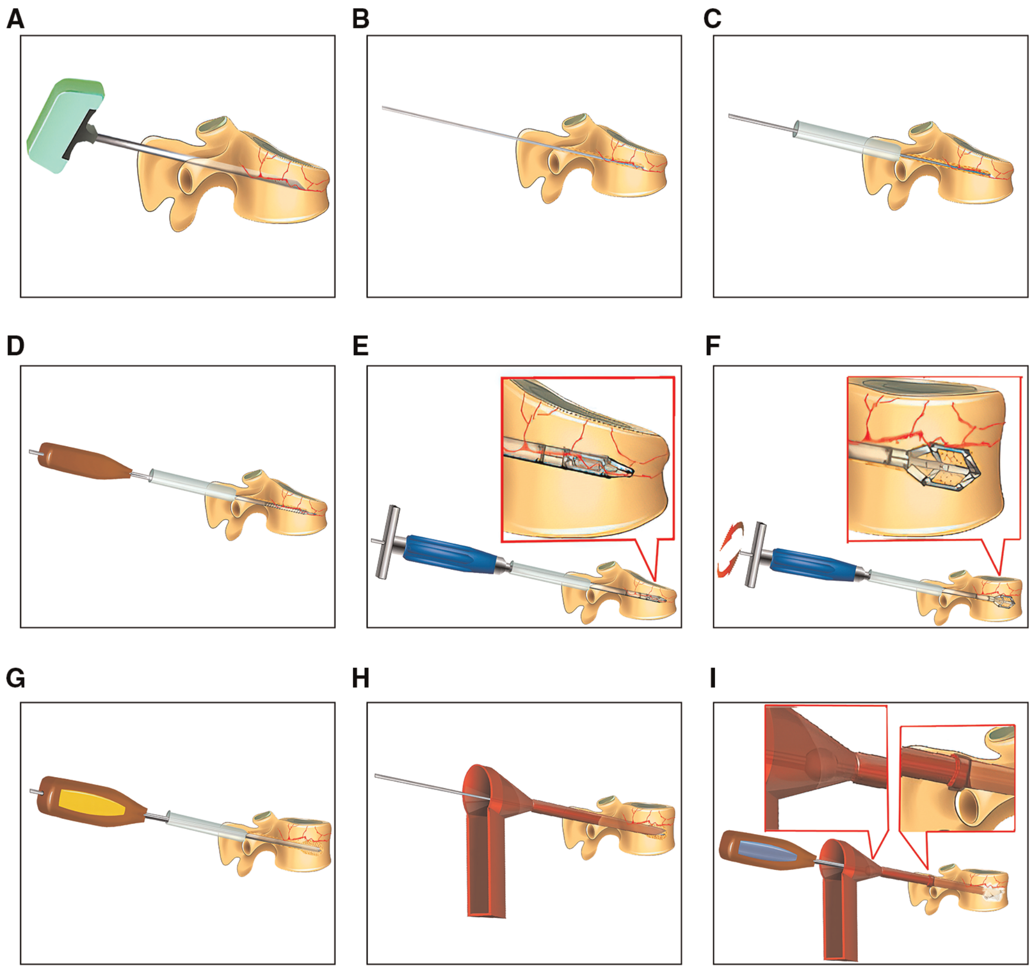

FIGURE 1
Illustration of PPSR procedures. (A) A puncture needle inserted into the appropriate depth of the fractured vertebra as examined by fluoroscopy. (B) A guide needle inserted into the vertebral body. (C) A hollow sleeve created to protect the surrounding soft tissues and guide the devices. (D) A rotary chisel applied to establish a channel for the percutaneous distractor. (E,F) The percutaneous vertebral distractor inserted into the fractured vertebra; the vertebral distraction was achieved by turning the percutaneous vertebral distractor. (G) A channel dilator was used to enlarge the channel for bone grafting. (H) Bone grafting through a funnel. (I) A bone grafting rod was used to push the bone graft materials into the injured vertebra. An accessory ball was applied to limit the depth range of the bone grafting rod. Range of the bone grafting rod.

Pedicle screws were implanted and their positions confirmed with fluoroscopy. The pre-bending rods were connected to pedicle screws, but not completely fixed. (3) Two longitudinal incisions (1.5–2 cm) were performed at 2 cm lateral to the projection area of the fractured vertebra pedicles. The novel distractor developed by our group was inserted into the fractured vertebra. The anterior end was close to the position of the superior endplate collapse. The collapsed endplates were distracted by turning the distractor. The same maneuver was carried out on the opposite side (4). Allogenous bone was used for bone grafting. A C-arm fluoroscopy revealed that the vertebral body height of the collapsed vertebra recovered and the rods were completely fixed with screws. The simulation diagram of the treatment outcome in patients underwent PPSR was presented (Figure 2). PPSR was used on a female patient with an L1 vertebral compression fracture and the

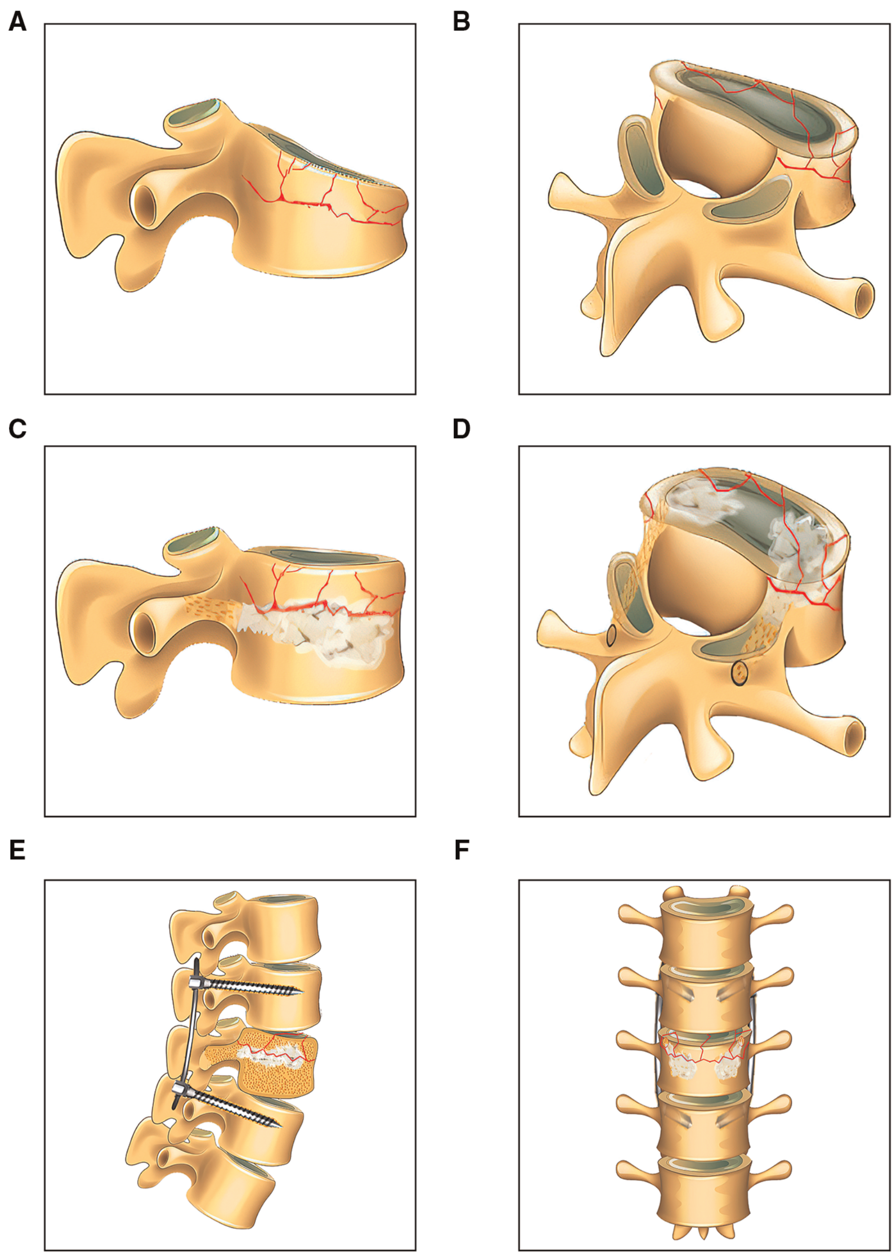

FIGURE 2
The simulation diagram of treatment outcomes in patients who underwent PPSR. (A,B) The preoperative sagittal and oblique diagram of the fractured vertebra. (C,D) The postoperative sagittal and oblique diagram of the vertebra. (E,F) The images of postoperative spinal segments in coronal and sagittal planes.

preoperative and postoperative radiographic images are presented in Figure 3. The AVH increased from 52.3% preoperatively to 98.8% postoperatively. The VWA decreased from 13.4° preoperative to 4.2° postoperative and the Cobb angle was corrected from 24.5° preoperatively to 6.3° postoperatively. No symptoms of discomfort were reported by the time of last follow-up. OPSF procedures are based on previously published literature (9).

Clinical parameters

Data collected from the medical records included age, gender, Body Mass Index (BMI), hypertension, diabetes, operative duration, blood loss, total incision length, postoperative stay, total hospitalization costs, fracture segment, the back and leg VAS score (0–10) and the Oswestry Disability Index (ODI) (0%–100%). VAS and ODI were collected at the time of admission, and at 1 week, 3 months, and 12 months after surgery through subsequent visit or telephone follow-up. All the clinical parameters were assessed by two junior attending physicians, and if their findings differed, a second opinion was sought from a senior physician.

Radiographic parameters

To evaluate the restoration of vertebral height and spinal curvature, the recovery rates of AVH, vertebral wedge angle (VWA), and Cobb angle were measured. The imaging findings were interpreted by two spine surgeons who had more than 10 years of clinical practice. If results from the two surgeons were inconsistent, the imaging findings would be evaluated by the professor with higher seniority in our team. Before surgery and 12 months after operation, all patients were subjected to radiographs, CT scans, and MRIs of the spine and the AVH, VWA, and Cobb angle were assessed. Recovery rates of AVH (%) = (postoperative AVH of the injured vertebra—pre-operative AVH of the injured vertebra)/[(AVH of the superior vertebra + AVH of the inferior vertebra)/2] (Figure 4). VWA was defined as the angle between superior and inferior endplates of the fractured vertebra (Figure 4). The Cobb angle was regarded as the angle between the upper endplate of T10 and the lower endplate of L2 on a lateral x-ray (Figure 4).

Statistical analysis

All the data were measured by at least two surgeons. Data in this study were analyzed by using SPSS (version 25.0) and Graphpad prism (version 8). Continuous variables were expressed as mean ± SD, and the enumeration data were was expressed as percentage. Independent sample t test was used for group comparisons for data, including BMI, operative duration, blood loss, incision length, total hospitalization costs, recovery rates of AVH, local Cobb angle, and VWA. Categorical variables were investigated by the χ^2 test. Normality was checked using the Shapiro–Wilk normality test. A two-sample *t*-test was used for normally distributed data, while Mann-Whitney *U* test was used for non-normally distributed data. A $P < 0.05$ was considered statistically significant.

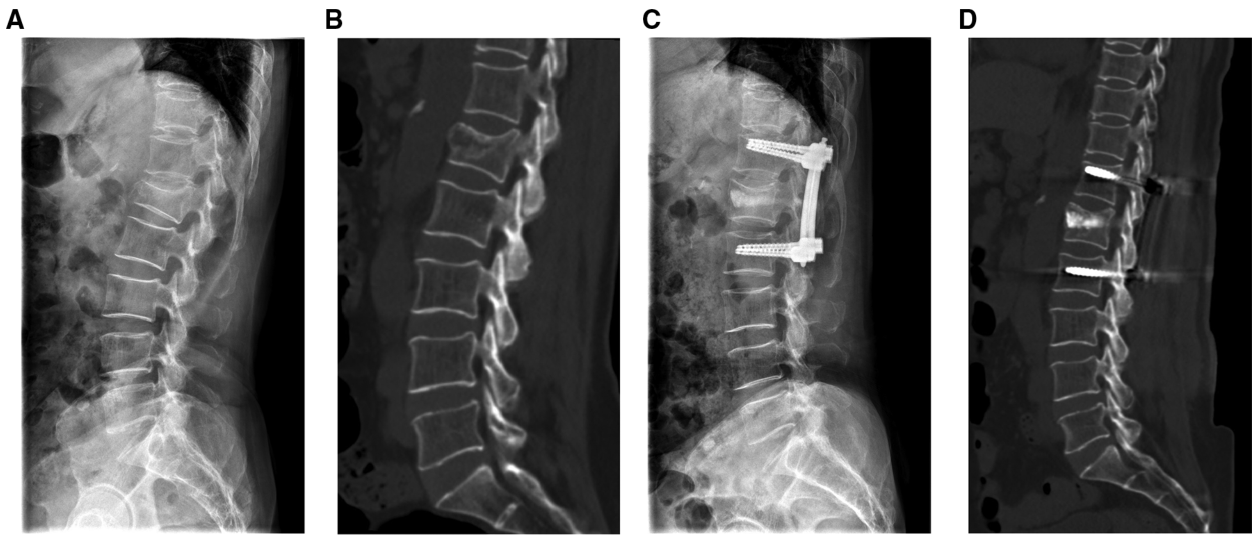

FIGURE 3
A patient treated with PPSR. (A,B) The preoperative sagittal radiograph (A) and CT image (B). (C,D) The postoperative sagittal radiograph (C) and CT image (D).

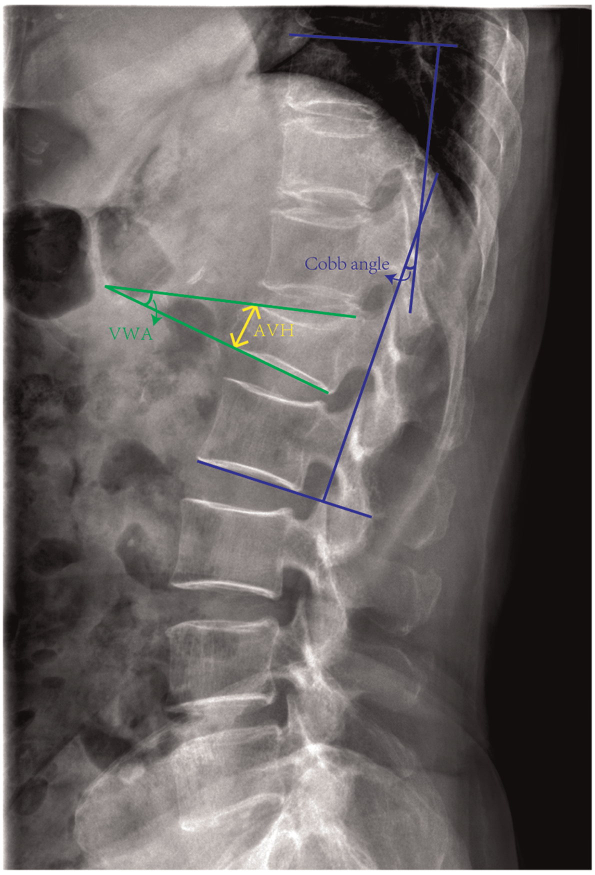

FIGURE 4
The definition of AVH, VWA and Cobb angle. The AVH refers to the height of the anterior vertebra. The VWA was defined as the angle between superior and inferior endplates of the fractured vertebra. The Cobb angle was considered as the angle between the upper endplate of T10 and the lower endplate of L2.

Results

Demographic and baseline characteristics

The demographic and baseline characteristics of the two groups were shown in Table 1. A total of 329 patients were included in this study. PPSR group had 153 patients (69 females and 84 males) and while the OPSF group 176 patients (81 females and 95 males). Average age of patients in the PPSR group at the time of surgery was 51.020 ± 11.540 and 52.181 ± 13.842 years in the OPSF group. There was no significant difference in baseline and demographic characteristics including gender, age, BMI, hypertension, diabetes, and fracture segment between the two groups (Table 1). T12 (24.836% in PPSR group and 26.136% in OPSF group) was the most frequently involved vertebra, followed by L1 (22.876% in in PPSR group and 22.159% in OPSF group).

TABLE 1 Demographic and baseline characteristics of the patients.

Variables	PPSR (n = 153)	OPSF (n = 176)	T value	P value
Gender (Female) n, %	69 (45.098)	81 (46.023)	0.028	0.867
Age, year	51.020 ± 11.540	52.181 ± 13.842	−0.82	0.413
BMI	25.844 ± 3.054	25.607 ± 3.776	0.622	0.535
Hypertension, n, %	25 (16.340)	28 (15.909)	0.011	0.916
Diabetes, n, %	18 (11.765)	22 (12.500)	0.041	0.839
Fracture segment, n, %				
T10	20 (13.072)	25 (14.205)	0.089	0.766
T11	28 (18.301)	33 (18.750)	0.011	0.917
T12	38 (24.836)	46 (26.136)	0.073	0.787
L1	35 (22.876)	39 (22.159)	0.024	0.877
L2	32 (20.915)	33 (18.750)	0.242	0.623
Types of fracture, n, %				
A1	83 (54.248)	98 (55.682)	0.068	0.794
A2	32 (20.915)	35 (20.231)	0.053	0.817
A3	38 (24.837)	43 (24.432)	0.007	0.932

Periprocedural characteristics of the patients in the PPSR group and the OPSF group

Perioperative data are shown in Table 2. Significant differences in features such as operation duration, blood loss, incision length, postoperative stay, and the total hospitalization costs were observed between the PPSR and the OPSF groups. Operative duration was 93.843 ± 20.611 min in PPSR group vs. 109.432 ± 11.903 min in OPSF group (P < 0.001). Volume of intraoperative blood loss was 131.118 ± 23.673 ml in PPSR group and 442.163 ± 149.701 ml in OPSF group (P < 0.001). The total length of skin incision was 7.280 ± 1.289 cm and 14.527 ± 2.893 cm in the PPSR group and the OPSF group (P < 0.001), respectively. The postoperative hospital stay of the patients was 8.732 ± 1.864 days in the PPSR and 15.102 ± 2.117 days in the OPSF group (P < 0.001). The cost of hospitalization in the PPSR group (59027.196 ± 8687.447 yuan) was significantly lower than that in the OPSF group (73144.432 ± 11747.567 yuan). Complications that were observed between the two groups did not differ considerably. Furthermore, no patients with single-level thoracolumbar fracture who received PPSR or OPSF experienced pulmonary embolism or bone material leakage after surgery.

Preoperative and postoperative radiographic results

The radiographic results of the PPSR group and the OPSF group were presented in the Table 3. The AVH was used to

TABLE 2 Periprocedural data for PPSR and OPSF groups.

Variables	PPSR ($n = 153$)	OPSF ($n = 176$)	T value	P value
Operative duration, min	93.843 ± 20.611	109.432 ± 11.903	−8.531	<0.001
Blood loss, ml	131.118 ± 23.673	442.163 ± 149.701	−25.421	<0.001
Incision length, cm	7.280 ± 1.289	14.527 ± 2.893	−28.610	<0.001
Postoperative stay, day	8.732 ± 1.864	15.102 ± 2.117	−28.770	<0.001
Total hospitalization costs, yuan	59027.196 ± 8687.447	73144.432 ± 11747.567	−12.237	<0.001
Complications				
Postoperative hematoma, n, %	1 (0.654)	2 (1.136)	0.211	0.646
Infection, n, %	1 (0.654)	3 (1.705)	0.753	0.386
Pedicle breach, n, %	2 (1.307)	1 (0.568)	0.495	0.482
Loose nut, n, %	2 (1.307)	1 (0.568)	0.495	0.482

TABLE 3 Preoperative and postoperative AVH, cobb angle, and VWA in PPSR and OPSF groups.

Variables	PPSR ($n = 153$)	OPSF ($N = 176$)	T value	P value
AVH				
Pre-operative, cm	1.477 ± 0.238	1.440 ± 0.167	1.648	0.100
12-months after surgery, cm	2.713 ± 0.176	2.231 ± 0.166	25.511	<0.001
Recovery rates of AVH	0.449 ± 0.079	0.279 ± 0.088	18.314	<0.001
Cobb angle, °				
Pre-operative	24.137 ± 0.573	24.128 ± 0.594	0.147	0.883
12-month after surgery	7.570 ± 1.422	12.631 ± 1.421	−32.191	<0.001
VWA, °				
Pre-operative	12.250 ± 2.562	12.568 ± 1.663	−1.349	0.178
12-months after surgery	6.747 ± 1.323	9.938 ± 1.385	−21.278	<0.001

estimate the severity of vertebra fracture and the recovery of the vertebral structure. The preoperative AVH was 1.477 ± 0.238 cm in the PPSR group and 1.440 ± 0.167 cm in the OPSF group, indicating that the pre-operative AVH between the two groups did not differ significantly ($P = 0.100$). The results of the AVH at 12-month after surgery demonstrated that the AVH in the PPSR group (2.713 ± 0.176 cm) was significantly higher than that in the OPSF group (2.231 ± 0.166 cm, $P < 0.001$). In addition, the recovery rate of AVH in patients that underwent PPSR (0.449 ± 0.079) was notably better than in patients who underwent OPSF (0.279 ± 0.088, $P < 0.001$). In addition, the degree of spinal kyphosis was evaluated by local Cobb angle. The preoperative Cobb angles between the two groups were statistically consistent ($P > 0.05$). The local Cobb angle at the 12-month after surgery between the PPSR group (7.570 ± 1.422°) and the OPSF group (12.631 ± 1.421°) was statistically significant ($P < 0.001$). Moreover, the VWA was also measured to further assess the efficacy of the surgeries used for the vertebral reconstruction. The preoperative VWAs of the two groups did not differ. The results showed that the VWA in the PPSR group (6.747 ± 1.323°) was greater than that in the OPSF group (9.938 ± 1.385°, $P < 0.001$). This finding demonstrated that PPSR are more effective than conventional OPSF in reconstructing fractured vertebra.

The clinical outcomes between the PPSR group and the OPSF group

The clinical outcomes were measured with VAS score and ODI score. There was no difference between the two groups at baseline in VAS score and ODI score. The mean VAS scores at the 3-day was PPSR, 3.88 ± 1.07; OPSF, 6.89 ± 1.13 ($P < 0.001$), 3-month was PPSR, 2.33 ± 0.78; OPSF, 4.88 ± 1.37 ($P < 0.001$), and 12-month was PPSR, 0.92 ± 0.82; OPSF, 3.36 ± 1.45 ($P < 0.001$). The VAS and ODI scores in the PPSR group were notably lower than that in the OPSF group on follow-up (**Figure 5A**). This difference in scores indicate that PPSR was more effective than OPSF in improving fracture-induced short-term pain and long-term pain. In addition, the ODI score results demonstrated that ODI scores were lower in the PPSR group than in the OPSF group at the time point of 3-day (PPSR, 0.36 ± 0.11; OPSF, 0.59 ± 0.11, $P < 0.001$), 3-month (PPSR, 0.29 ± 0.11; OPSF, 0.44 ± 0.08, $P < 0.001$), and 12-month (PPSR, 0.22 ± 0.11; OPSF, 0.31 ± 0.08, $P < 0.001$) after surgery (**Figure 5B**). The results demonstrated that the quality of life of patients in the PPSR group was better than that of patients in the OPSF group.

Discussion

Spine fracture injuries are quite common, with most occuring at thoracolumbar junction. According to an international statistic report, approximately 5% of spine fractures, and 54.9% thoracolumbar fractures inflict substantial financial burden (1, 10). Generally, treating most thoracolumbar fractures with neurologic deficits surgically is accepted widely (11). If no neurological dysfunction or instability of thoracolumbar fracture is observed in patients with

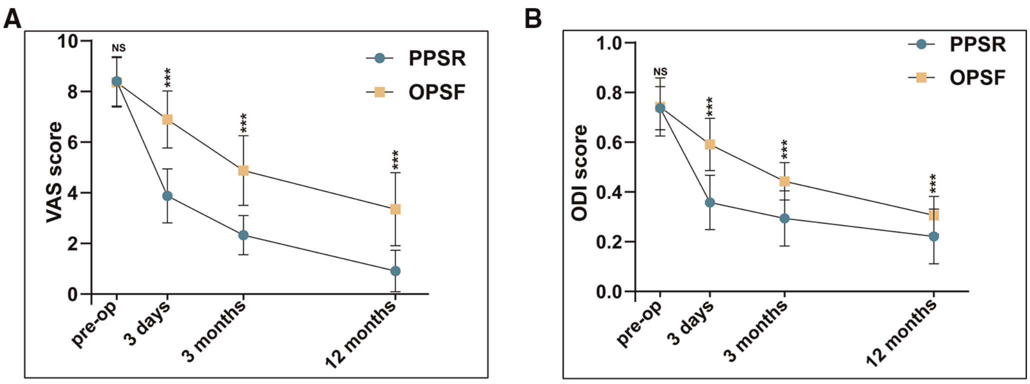

FIGURE 5
Comparison of clinical outcomes between the PPSR group and OPSF group. (A) The VAS scores between the PPSR group and OPSF group. (B) The ODI scores between the PPSR group and OPSF group. NS indicates no significance. Data are presented as the mean ± SD. *: $P < 0.05$, **: $P < 0.01$, ***: $P < 0.001$.

thoracolumbar fractures, surgical intervention is not recommended. However, restoring the vertebral height and correcting the spinal kyphosis is indicated when the AVH loss exceeds 50% or when the local Cobb angle is greater than 15°–20° (12). OPSF is performed through stripping of paraspinal muscles, bilateral erector spine and multifidus muscles to expose vertebral plates, zygapophyses and transverse processes in thoracolumbar fracture. Although clinical symptoms can be significantly improved, a series of events such as intractable pain, stiffness, and weakness occur after the OPSF operation because of the denervation of the muscles, extensive adhesion and scar formation (9). Furthermore, OPSF plays a role in restoring the AVH and correcting the Cobb angle which is performed *via* longitude traction of the titanium rod. However, OPSF cannot effectively reduce the vertebrae fracture. These disadvantages have limited the wide use of OPSF in thoracolumbar fractures.

Over the last decades, minimally invasive spinal surgery has received increased attention. In 1984, Magerl firstly described the concept of percutaneous pedicle screw fixation (4). Percutaneous transpedicular screw fixation has fewer side effects on paraspinal muscles and can results in faster recovery than open fixation. After several improvements, Assaker reported that capability of percutaneous transpedicular fixation for treating thoracolumbar fractures (13). This technique became popular in treating thoracolumbar fractures because of the unique advantages such as shorter operative time, less blood loss, minor wound, and mild pains. It was reported that all 36 patients with thoracolumbar fractures who underwent minimally invasive percutaneous transpedicular fixation achieved satisfactory outcomes (14). However, the conventional percutaneous transpedicular technique uses Sextant's percutaneous fixation system that is less effective in reducing fractured vertebra than the open reduction internal fixation system (15). Generally, minimally invasive surgery is not recommended for patients with thoracolumbar fractures, who had greater than 50% vertebral height reduction since kyphosis cannot be adequately reduced (16). For thoracolumbar fractures without neurological deficit, decompression is not needed and the surgical intervention is focused on the restoration of the injured vertebra height and the correction of the spinal kyphosis caused by the fractured vertebra (9). For patients with thoracolumbar fractures, the decreased height of the vertebra can lead to changes in the sagittal spinal alignment and the spinal biomechanics. The increase in the kyphotic angle is a contributor to the instability of the fractured spinal segment and aggravates the deformity (17). Restoring the vertebral height and correcting the spinal kyphosis make sense when the AVH loss exceeds 50% or the local Cobb angle is greater than 15°–20° (12). However, the use of conventional percutaneous transpedicular fixation system cannot achieve these goals completely.

To address these concerns, PPSR, a novel minimally invasive internal fixation system was developed based on the conventional percutaneous transpedicular screw fixation system. PPSR was developed to restore and maintain the height of the injured vertebra and correct the spinal kyphosis resulting from vertebra fracture. PPSR can reconstruct the anterior column of the fractured vertebra by distracting the vertebra and transplant bone into the fractured vertebra. There are apparent advantages of using PPSR for treating thoracolumbar fractures without neurologic deficits. Firstly, the peroperative preoperative data in this study indicated that the operation duration, blood loss, postoperative stay, and the total costs of hospitalization in the PPSR group were notably lower than that in the OPSF group (18). The rate of complications between the two groups was similar, indicating the PPSR procedure had a safety profile that was manageable. Our results are similar with those of previous studies that have revealed that minimally invasive surgery result in various advantages such as shorter operation time, less blood loss, reduced hospital stay, decreased infection rate, and faster motor recovery (16). Secondly, the recovery rates of AVH of patients who underwent PPSR were significantly higher than that of patients in the OPSF group. The Cobb angle and the VWA results revealed that PPSR reduced kyphosis caused by the fractured vertebra. Both the recovery of the AVH and the correction of the Cobb angle and VWA in patients who underwent PPSR benefited from not only the titanium rods and screws (indirect longitudinal distraction) but also the bone transplantation in the fractured vertebra (direct distraction). In this present study, PPSR was more efficient in restoring AVH and improving the fracture-induced by spinal kyphosis than OPSF. This may be because OPSF was designed to achieve vertebral reduction only through the indirect longitudinal distraction effect of the titanium rods and screws. PPSR can restore spinal stability through restoring vertebral height and enhancing the biomechanical strength of the fractured vertebra. Early loss of correction following short-segment pedicle screw fixation (19) has been reported in a previous study. This finding differs with our study, where early loss of correction after PPSR or OPSF was not observed. Although clinical outcome observed during the follow-up period was satisfactory, longer duration of follow-up would also be beneficial.

Besides PPSR, there is a traditional kyphoplasty with percutaneous screw fixation that has long been used in treating thoracolumbar fractures (20). Although PPSR and the traditional kyphoplasty with percutaneous screw fixation utilize similar processes, PPSR has huge advantages. Firstly, bone graft materials that were used in PPSR have great osteoinductive potential that contribute to the bone healing of fractured vertebra, but the bone cement used in the kyphoplasty with percutaneous screw fixation cannot promote healing. Secondly, the incidence of the degeneration of the intervertebral discs in the adjacent segments in patients who accepted bone cement augmentation was high (21), due to weaker buffering role of bone cement than bone graft materials. Thirdly, the distraction of the fractured vertebra in the PPSR is slow and even cause in stable and reliable distraction effect. On the other hand, this distraction effect of the traditional kyphoplasty with percutaneous screw fixation is transient and elastic and it cannot achieve satisfactory distraction effect. Lastly, PPSR can significantly reduce medical costs because PPSR devices are not one-time medical consumable materials. Therefore, we believe that PPSR could provide great benefits to households and the society.

Initially, fixing of the spinal column involved the whole spine. With the development of concepts and technologies has led to focusing of fixation on the adjacent vertebrae of the involved segments rather than the whole spinal column. Then, to achieve a more precise therapeutic effect, Denis proposed the concept that the spinal column could be divided into three parts: anterior column, middle column, and posterior column (22). The development of this concept was from overall spinal column to the local segment. Consistently, based on the previous research findings, the newly-developed PPSR technique focuses on reconstructing the anterior column that comprises a key part of the spine. Data from this study has efficiently demonstrated the safety and efficacy of PPSR. PPSR is more effective than OPSF in improving the clinical outcomes of patients with thoracolumbar fractures by restoring vertebral height and correcting kyphosis more reliably.

Nevertheless, there are also some limitations in this study. Cases included in this study were patients with single-segment fracture, and therefore at present the role of PPSR in treating more complicated thoracolumbar fractures has not been elucidated. In addition, the evidence level of this retrospective study was quite low. A prospective, multicenter randomized clinical trial should be carried out. Moreover, other variable that may influence the therapeutic effect of PPSR, such as the causes of fracture and other types of fracture were not considered in the study. Also, the one-year follow-up period of this study was relatively brief. A longer follow-up period would have helped our team to obtain more precise results.

Conclusions

In conclusion, the novel PPSR has a safety profile similar to OPSF. It is worth noting that PPSR restores the vertebral height and the spinal kyphotic angle better than the conventional open internal fixation. Thus, PPSR is a reliable option for treating thoracolumbar fractures.

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 the Wujin Hospital of Traditional Chinese Medicine. 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

LNR and SCH conceived and designed the study. FDL, CC, YCW, YHY, YFL, and JL collected data. LNR, FDL and CC analyzed the data and prepared figures and tables. FDL and LNR wrote the manuscript. FDL revised the manuscript. The authors all read and approved the final manuscript.

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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.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsurg.2022.1039054/full#supplementary-material.

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A novel surgical management for pediatric patients with irreducible atlantoaxial dislocation: Transoral intraarticular cage distraction and fusion with C-JAWS staple fixation

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Background: Currently, irreducible atlantoaxial dislocation (IAAD) can be treated by a single transoral approach in one stage to reduce surgical injuries to patients. However, the widely used fixation devices are not suitable for pediatric patients because of larger profile of devices.
Objective: The purpose of this study is to report the preliminary clinical outcomes of a novel surgical technique by transoral intraarticular cage distraction and fusion with C-JAWS staple fixation for pediatric patients with IAAD.
Methods: From June 2011 to June 2014, eight pediatric patients with IAAD were enrolled and treated by this technique in our department. Patients' clinical data were retrospectively analyzed, including neurological status, clinical symptoms, reduction, bone fusion, and complications.
Results: The surgeries were successfully performed in all patients without injuries to spinal cord, nerve and blood vessel. Clinical symptomatic relief was presented on all 8 patients (100%). Satisfactory reduction was indicated by significant decrease of atlanto-dental interval postoperatively ($P < 0.05$). The remarkable improvement of postoperative neurological function has been proved by significant increase of Japanese Orthopaedic Association score ($P < 0.05$). The average follow-up duration was 19.4 ± 5.8 months (range 12–30 months). Bone fusion was achieved in all 8 cases. No complications were documented after operation and during follow-up.
Conclusions: Transoral intraarticular cage distraction and fusion with C-JAWS staple fixation is an effective treatment for pediatric patients with IAAD, which can achieve satisfactory reduction, fixation and bone fusion.

KEYWORDS
irreducible atlantoaxial dislocation, transoral approach, reduction, internal fixation, spinal fusion

Introduction

Atlantoaxial dislocation is a common disease in the craniocervical junction, which can be caused by inflammation, tumor, trauma, congenital malformation, degeneration and other factors. This disease can cause neck pain, numbness and weakness in the limbs, hemiplegia and other symptoms, and can be life-threatening in severe cases (1). According to Yin et al.'s classification system, the atlantoaxial dislocation is divided into reducible dislocation, irreducible dislocation and fixed dislocation based on the degree of difficulty in reducing the dislocation, which determines the surgical choices (2).

Surgical treatment of irreducible atlantoaxial dislocation (IAAD) commonly requires transoral release plus posterior reduction and fixation (3). For pediatric patients with IAAD, more injuries may be caused by anteroposterior surgery. After performing transoral anterior release, the position change from supine to prone would increase the risk of spinal cord injury due to extreme atlantoaxial instability (4). Anteroposterior surgery can result in more soft tissue damage and bleeding. Currently, the single transoral approach can achieve release, decompression, reduction, fixation and fusion for IAAD in one stage (5). However, the present fixation devices, like the well-known transoral atlantoaxial reduction plate (TARP) (6), have a larger shape, which is not suitable for pediatric patients in most situations (4). The C-JAWS, a cervical compressive staple, with a smaller shape, has been used in anterior cervical discectomy and fusion (ACDF) but not in the atlantoaxial joint. In this study, a novel surgical technique by transoral intraarticular cage distraction and fusion with C-JAWS staple fixation was performed in 8 pediatric patients with IAAD, and the clinical data were retrospectively analyzed to evaluate the clinical effects of this technique.

Materials and methods

Patients

From June 2011 to June 2014, a total of 8 pediatric patients (3 boys and 5 girls, 10.0 years old on average, range 8–12) with IAAD underwent transoral surgeries using an intraarticular cage and C-JAWS staple (**Table 1**). The average disease duration was 10.5 ± 6.6 months (range 3–24 months). The clinical symptoms were as follows: progressive extremity numbness (8/8, 100%), extremity weakness (6/8, 75.0%), occipitocervical pain (5/8, 62.5%), unsteady gait (2/8, 25.0%), and hemiparesis (1/8, 12.5%) (**Table 2**).

Preoperative examinations

Before surgery, plain cervical radiographs, computed tomography (CT) scans and magnetic resonance imaging

TABLE 2 Clinical symptoms.

Symptoms	Preoperative no. (%)	Postoperative improvement no. (%)
Occipitocervical pain	5 (62.5%)	5 (100%)
Extremity numbness	8 (100%)	7 (87.5%)
Extremity weakness	6 (75.0%)	5 (83.3%)
Unsteady gait	2 (25.0%)	2 (100%)
Hemiparesis	1 (12.5%)	1 (100%)

Each patient may have one or more symptoms.

TABLE 1 Pre- and postoperative data of the 8 patients.

Case	Age (year)/Sex	Duration of symptom (month)	ADI (preop)	ADI (postop)	JOA (preop)	JOA (postop)	Bone fusion confirmed (month)	Follow-up (month)	Complication
1	12/M	24	8.5	2.1	11	15	6	15	No
2	10/F	15	7.3	1.5	10	14	6	18	No
3	8/M	8	9.8	2.5	8	12	3	24	No
4	9/F	6	6.4	0.5	8	14	6	30	No
5	12/F	3	7.1	1.0	10	15	3	20	No
6	11/M	12	8.2	1.5	9	12	6	12	No
7	10/F	6	5.2	0	11	15	3	15	No
8	8/F	10	6.6	0.8	13	16	6	21	No
M ± SD		10.5 ± 6.6	7.4 ± 1.4	1.2 ± 0.8	10.0 ± 1.7	14.1 ± 1.5		19.4 ± 5.8	
T			27.025		−11.773				
P			0.000[a]		0.000[a]				

F, female; M, male; ADI, atlanto-dental interval; JOA, Japanese Orthopedic Association score; M ± SD, mean ± standard deviation.
[a]Paired-sample *t*-test.

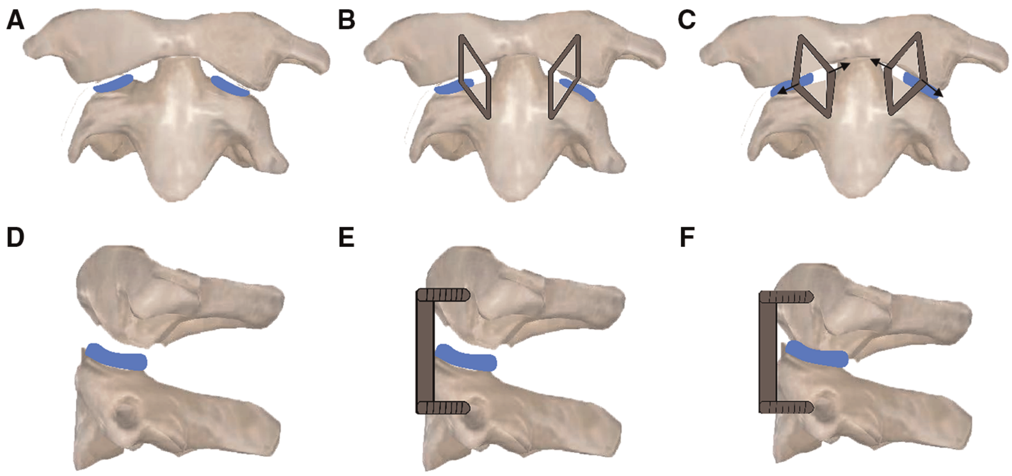

FIGURE 1
Schematic diagram of operation. (A,D) Two intraarticular cages were inserted into the bilateral lateral mass joints. (B,E) Two C-JAWS staples were fixed to the atlantoaxial joint, with the cephalad end fixed into the C1 lateral mass and the caudal end fixed into the C2 vertebral body. (C,F) Two C-JAWS staples were spreaded to both sides to produce compression on joints.

(MRI) were performed for all patients. Two cases were complicated with old odontoid fracture, 4 cases with basilar invagination, and 2 cases had undergone posterior surgery. All patients have undergone skull traction in a hyperextended position for one week. The weight of skull traction is 1/12 to 1/10 of body weight. All 8 cases were diagnosed as IAAD, for which AAD could not be restored by traction. MRI showed obvious compression of the cervical cord in all of the cases. The average Japanese Orthopaedic Association (JOA) score (17-point system) was 10.0 ± 1.7, and atlanto-dental interval (ADI) was 7.4 ± 1.4 mm.

Surgical procedure

Preoperative preparations: An oral examination and dental cleaning were performed before surgery. Oral cleaning with 0.02% vinegar chlorhexidine was performed 3–6 times per day for 3 days before surgery. Broad-spectrum antibiotics were administered intravenously 30 min before surgery.

Surgical techniques: Under general anaesthesia with nasotracheal intubation, the patient was placed in supine position with skull traction of 4–6 kg. After disinfection of the oral cavity, a middle longitudinal incision was made in the posterior pharyngeal wall. The mucosa and muscle were then separated to expose the C1 anterior arch, C2 vertebral body and bilateral lateral mass joints. Then, the anterior scar tissue and hyperplastic callus between the odontoid and anterior arch were resected. After incision of the capsules of bilateral lateral mass joints, the intraarticular adherent tissues and articular cartilage were removed with a curette and grinding drill to completely loosen the atlantoaxial joint. Two intraarticular cages (Wego, Shandong, China) filled with autologous iliac bone were then inserted into the bilateral lateral mass joints for distraction and bone fusion (Figures 1A,D, 2A). Afterwards, reduction of the atlantoaxial joint and well-placement of cages were identified by intraoperative x-ray (Figure 2B), two appropriate C-JAWS staples (Medicrea, Lyon, France) were used to fix the atlantoaxial joint, with the cephalad end fixed into the C1 lateral mass and the caudal end fixed into the C2 vertebral body (Figures 1B,E), and a slight compression was applied at the holders by spreading it to both sides (Figures 1C,F, 2C). The length of the nail portion of the C-JAWS staple is 12–18 mm. Afterwards, reduction of the atlantoaxial joint and the desired position of implantation were further confirmed by intraoperative x-ray (Figure 2D). Eventually, the wound was closed in layers.

Postoperative management and follow-up

The nasal trachea cannula was removed in 24–48 h postoperatively, and the nasogastric tube was removed on day 7 postoperatively. Ultrasonic nebulisation and 0.02% chlorhexidine acetate gargling were performed 3–6 times per day for 7 days. Broad-spectrum antibiotics were administered introvenously for 3 days. The cervical x-ray, CT scan and MRI were performed postoperatively. The ADI was measured to evaluate the reduction of C1–C2. The patients' neurological status was assessed using the JOA score. Bone fusion was confirmed by CT scan. All patients were asked to wear a rigid Philadelphia cervical collar for 3 months and were followed

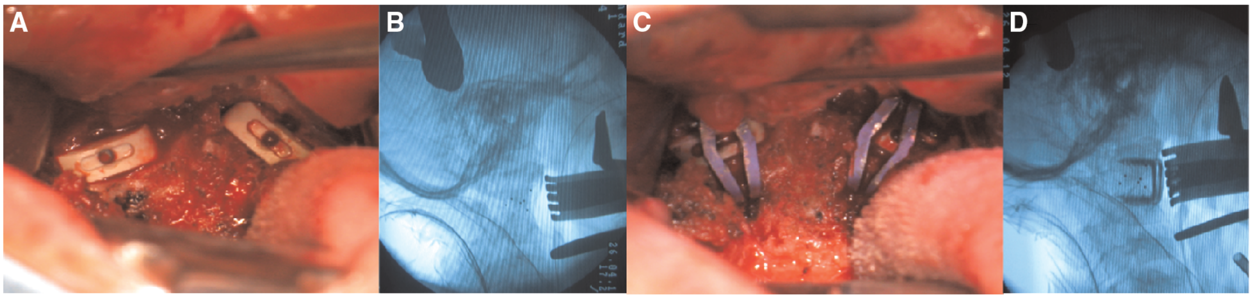

FIGURE 2
Intraoperative procedures. (**A,B**) The bilateral intraarticular cages were implanted and intraoperative fluoroscopy showed satisfactory atlantoaxial reduction. (**C,D**) Two C-JAWS staples were fixed and intraoperative fluoroscopy showed satisfactory location of holders.

up at 3, 6, 9 and 12 months and then once per year. If bone fusion was not achieved, patients needed to keep wearing the cervical collar until confirmation of bone fusion.

Statistical analysis

SPSS 21.0 software (IBM, Armonk, NY, United States) was used for the statistical analysis. The K-S test was used to verify the normal distribution of data. All data were expressed as mean and standard deviation. ADI and JOA scores before and after surgery were compared using paired-sample *t*-test, and *P*-value <0.05 was considered statistically significant.

Results

Surgeries on 8 cases were performed successfully. The average operative time was 152.5 ± 32.0 min (range 110–200 min), with average intraoperative blood loss of 77.5 ± 22.5 ml (range 50–110 ml). No spinal cord, vascular or duramater injuries occurred during the operation. Clinical symptoms were relieved in all patients (**Table 2**). The average follow-up time was 19.4 ± 5.8 months (range 12–30 months). Satisfactory reduction of C1–C2 were achieved in all cases shown on postoperative radiographs and CT scans, with a marked reduction of postoperative ADI (1.2 ± 0.8 mm) compared to preoperative ADI (7.4 ± 1.4 mm, $P < 0.05$). Decompression of spinal cord were found on postoperative MRI (**Figure 3**). Postoperative neurological function was significantly improved, with significant improvement of JOA score from preoperative 10.0 ± 1.7 to postoperative 14.1 ± 1.5 ($P < 0.05$). All of the cases obtained bone fusion in 3–6 months after operation. No complications of re-dislocation or neurological deterioration were documented after operation and during the follow-up.

Discussion

IAAD usually results in spinal cord compression and profound neurologic deficits. Therefore, a surgical therapy is imperative to obtain symptoms alleviation and spinal cord decompression (1). It is a common view that transoral release plus posterior reduction, fixation and fusion is necessary for surgical treatment of IAAD (3, 7, 8). But an anteroposterior approach can cause more surgical trauma, especially performed on pediatric patients. Moreover, after performing transoral release, the risk of spinal cord injury would be increased when changing patient's posture because of the extremely unstable atlantoaxial joint (9).

Currently, a single transoral approach can achieve release, decompression, reduction, fixation and fusion for IAAD in one stage to reduce surgical trauma to patients (5). The transoral atlantoaxial reduction plate (TARP), a well-known transoral technique, designed by our institution in 2004, can achieve release, reduction, decompression, fixation and fusion in one stage through a single transoral approach, that provides an effective surgical approach for the treatment of IAAD accompanied by spinal cord compression (5, 6, 10, 11). But, according to our clinical experience, the thicker thickness and large shape of the TARP make it difficult to conveniently accomplish the surgical procedures in most pediatric patients with limited oral space and smaller anatomical structure (4). Additionally, the insufficient soft tissues of the pharyngeal wall to cover the plate potentially leads to the occurrence of postoperative dysphagia and disruption of wound (5, 6).

The C-JAWS, a cervical compressive staple, has a thinner thickness of 1.5 mm and smaller shape than common anterior cervical plate, and has been commonly used for intervertebral compression fixation after implantation of interbody cage in ACDF. Fiere et al. (12) reported a dependable biomechanical stability of C-JAWS staple in a vitro testing and the early clinical results of 23 cases who underwent ACDF using an interbody cage and C-JAWS staple showed various advantages

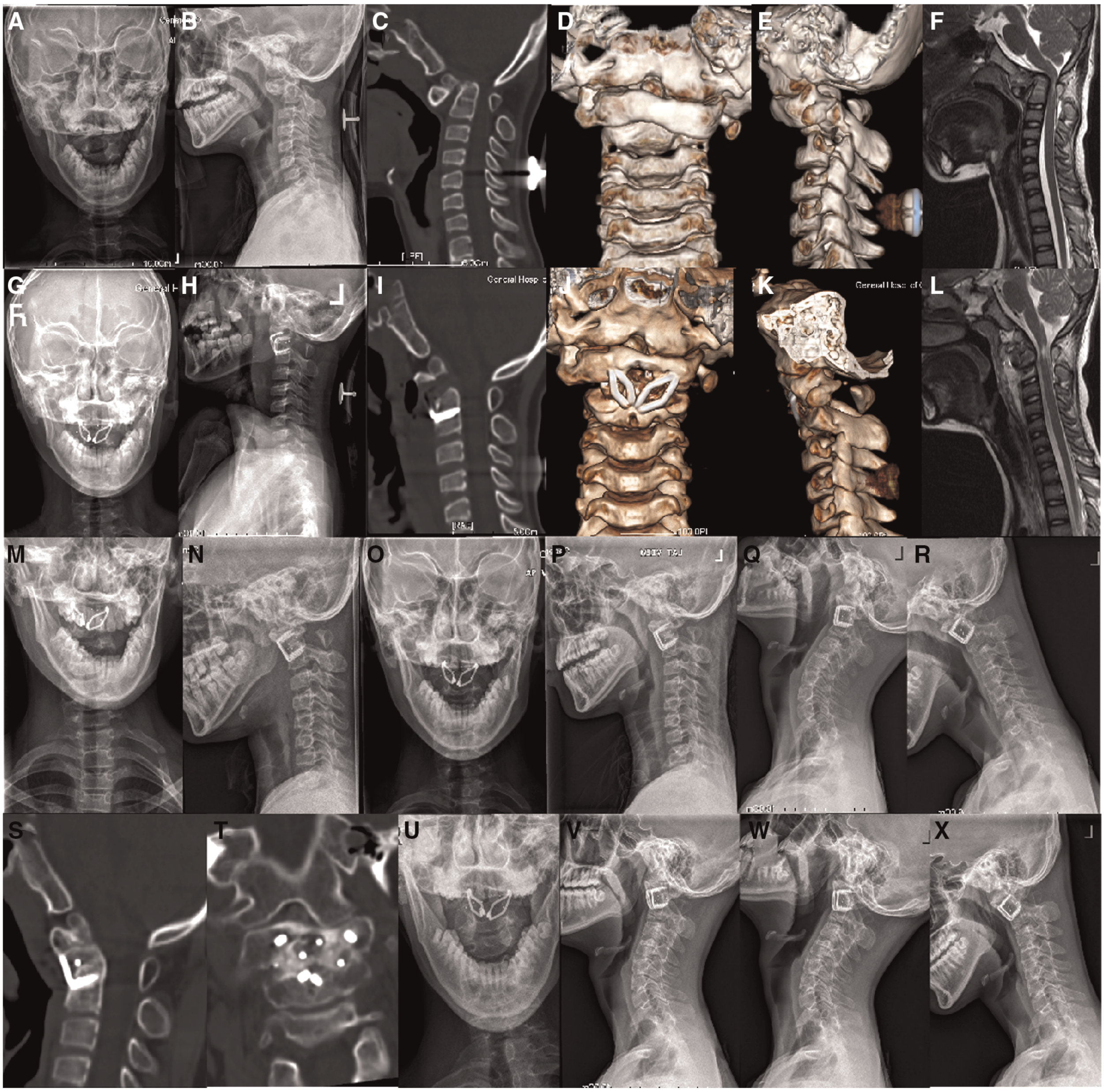

FIGURE 3
A 12-year-old boy, who was diagnosed IAAD with old odontoid fracture, underwent transoral intraarticular cage distraction and fusion with C-JAWS staple fixation. (A–E) Preoperative cervical x-rays and CT scans with three-dimensional reconstruction showed evidence of IAAD with old odontoid fracture. (F) Preoperative Sagittal MRI revealed compression of the spinal cord. (G–K) Cervical x-rays and CT scans with three-dimensional reconstruction performed at 1 week after revision surgery showed satisfactory reduction and good placement of fixation and cages. (L) Postoperative sagittal MRI showed a desirable decompression of the spinal cord. (M,N) Cervical x-rays at 3-month follow-up showed stable fixation. (O–R) Cervical x-rays at 6-month follow-up showed stable fixation without loss of reduction. (S,T) CT scans at 6-month follow-up revealed a solid bone fusion. (U–X) Cervical x-rays at last follow-up showed good C1–C2 sequence.

including short incision, short operative time and lower rate of dysphagia incidences as compared to most of the anterior cervical plate. Xia et al. (13) presented the similar result of 9 cases who underwent ACDF with an interbody cage and C-JAWS staple. The authors believed that the usage of the C-JAWS staple when performing transoral fixation after implantation of intraarticular cage to atlantoaxial joint would be simplify the surgical procedure, reduce the wound tension and operative trauma, which benefited from its thinner and smaller shape.

In this study, we reported a novel surgical technique by transoral intraarticular cage distraction and fusion with

C-JAWS staple fixation in 8 pediatric patients with IAAD. The C-JAWS staple was used to stabilize bilateral lateral mass joints of C1–C2 after placement of intraarticular cage and evaluated the clinical effects. All patients achieved satisfactory reduction, reliable fixation, improvement of neurological function and bone fusion without complications during the operation and the follow-up.

Limitations

Several limitations in the current study should be noted. Firstly, the sample size is ratter small. With larger cases performed on this technique, the clinical efficacy may be more thoroughly evaluated. Secondly, this is a retrospective study. Further prospective studies need to better control the follow-up intervals and require more standardized measurements.

Conclusion

Transoral intraarticular cage distraction and fusion with C-JAWS staple fixation is an effective and safe surgical option to treat IAAD in pediatric patients. The use of intraarticular cage can distract the atlantoaxial joint to obtain satisfactory reduction and facilitate bone fusion, and the C-JAWS staple can provide reliable fixation, that offers a new method for anterior atlantoaxial fixation through a transoral approach in pediatric patients.

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 General Hospital of Southern Theatre Command of PLA. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

XZ Conceptualization, Methodology, Writing - Original Draft. HY Conceptualization, Methodology, Writing-Original Draft. SF Conceptualization, Methodology. CD Validation, Formal analysis. JC Validation, Formal analysis. RM Software, Visualization. XM Writing-Review & Editing. ZW, XZ Conceptualization, Methodology, Writing-Review & Editing. 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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Comparison of C2 dome-like laminectomy with C2 partial laminectomy for upper cervical ossification of the posterior longitudinal ligament

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Objective: To compare surgical outcomes of C2 dome-like laminectomy with C2 partial laminectomy in patients with ossification of the posterior longitudinal ligament (OPLL) up to the C2 level and above.
Methods: 32 patients underwent surgical treatment for OPLL up to C2 and were divided into: C2 dome-like laminectomy group (C2-DOM group, $n = 16$) and C2 partial laminectomy group (C2-PL group, $n = 16$). The cervical curvature (CCI), dura width at C2/3, Japanese orthopedic association (JOA) score, recovery rate (RR), neck disability index (NDI) score, and visual analogue scale (VAS) score were evaluated and compared preoperatively and postoperatively at 1 month, 3 months, 6 months, 1 year, and annually thereafter.
Results: The JOA score and NDI significantly improved at the final follow-up in both groups with no significant intergroup differences. There were no significant differences in preoperative dura width at C2/3 and VAS between the two groups. At the final follow-up, dura width at C2/3 in the C2-PL group was significantly larger than the C2-DOM group, while the VAS of C2-DOM group was significantly lower than C2-PL group. The CCI in both groups decreased compared with before surgery, and there was no significant difference in CCI between the two groups.
Conclusion: C2-DOM is less demolitive and reduces postoperative neck pain, while C2-PL can achieve more adequate decompression without increasing the risk of postoperative cervical kyphosis.

KEYWORDS

OPLL, cervical spine, c2 partial laminectomy, c2 dome-like laminectomy, axial symptoms

Introduction

Ossification of the posterior longitudinal ligament (OPLL) of the cervical spine was first reported by a Japanese physician in 1960 (1). It is an ossifying hyperplasia of the posterior longitudinal ligament of the spine, which can be accompanied by severe neurological dysfunction. OPLL is frequently reported in men, in the elderly, and in Asian populations, and its pathogenesis remains elusive. The occurrence and development of OPLL are caused by combination of factors, including genetic factors, endocrine factors, and mechanical stimulation (2, 3) Surgical decompression is required when the ossified posterior longitudinal ligament compresses the cervical spinal cord and causes severe clinical and neurological symptoms. Anterior or posterior surgery both achieved effective decompression of the spinal cord and reduced patients' neurological symptoms (4). OPLL is mainly located below the C2 segment. For OPLL involving more than three levels and located below the C2 level, C3–7 single open-door laminoplasty or laminectomy with instrumented fusion are the most common posterior surgical options (5). However, the upper cervical OPLL is often identified in cases of continuous type and mixed type of OPLL, and the narrowest space is typically found in the C2–C4 segment (6). Decompression surgery below C2 alone for upper cervical OPLL may lead to inadequate decompression, thus possibly resulting in unsatisfactory surgical outcomes and persistence of neurological symptoms due to C2–C3 stenosis. Therefore, surgical decompression above C2 segment is necessary, although direct decompression through the anterior approach is difficult and risky (6). C2 dome-like laminectomy (C2-DOM) and C2 partial laminectomy (C2-PL) are commonly used posterior approaches of C2 decompression (7–9). However, few studies have compared the efficacy of these two surgical methods. Therefore, the present study aimed to compare the surgical outcomes of C2-DOM with C2-PL for the treatment of upper OPLL and to provide evidence for making clinical decisions.

Materials and methods

Patients

This retrospective study included 32 patients who underwent surgery for OPLL of the cervical spine above the C2/3 intervertebral disc at the Third Hospital of Hebei Medical University (Shijiazhuang, China) between January 2016 and January 2020. OPLL was diagnosed based on the computed tomography (CT) and magnetic resonance imaging (MRI) findings for all patients. The inclusion criteria were as follows: (1) Ossified segment of the posterior longitudinal ligament involving the C2 vertebral body and below; (2) C2-DOM or C2-PL (3) Complete preoperative and postoperative follow-up clinical data; (4) Follow-up ≥24 months. The exclusion criteria were as follows: (1) Ossification of the cervical ligamentum flavum; (2) Combination of OPLL of the thoracic and lumbar spine; (3) Patients who were diagnosed with OPLL combined with cervical fractures, deformities, tumors, infections, etc.; (4) History of previous cervical spine surgery.

Surgical procedures

All surgeries were performed by the same surgical team. After general anesthesia, the patient was placed at a standard prone position and the head was fixed with a skull traction tong. Standard disinfection of the surgical area and sterile draping were performed.

A midline posterior incision was made between the C2 and T1 spinous processes and paravertebral muscles were dissected to expose posterior elements. All patients underwent standard laminectomy with instrumented fusion from C3 downwards to C7. In the C2-DOM group, a high-speed drill was used to resect a part of the ventral lamina in an arc below the bottom of the C2 spinous process, and the ligamentum flavum was removed until the cervical spinal canal was decompressed. The resection width of the ventral lamina of C2 should be based on the width of the dura mater, and excessive cortical resection should not be performed to avoid C2 spinous process fractures (**Figure 1**). Eventually cervical paravertebral muscles were reattached to the C2 spinous process. In the C2-PL group, partial laminectomy was performed with a Kerrison rongeur until the lower third or two thirds of the C2 lamina and spinous process were removed (**Figure 2**). Approximately 5 mm of lamina were removed, along with part of the residual ventral lamina until the dura was decompressed (**Figure 3**). The ventral ligamentum flavum was removed by Kerrison rongeur until the dura was no longer compressed.

All patients wore a Philadelphia collar for 2–4 weeks after surgery, and then, they started moderately functional exercise of the neck.

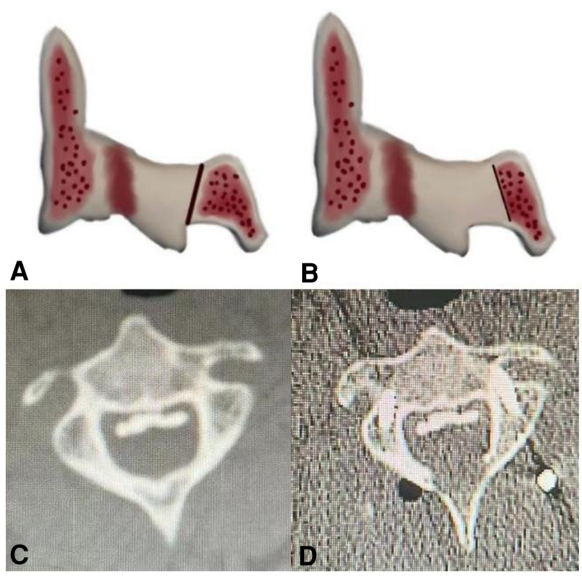

FIGURE 1
Schematic diagram of C2 dome-like laminectomy (C2-DOM). (**A,B**) The ossification of the posterior longitudinal ligament (OPLL) up to C2. (**C,D**) The C2 after dome-like laminectomy. (the ligamentum flavum and the ventral part of the lamina were removed).

Assessment of outcomes

All patients underwent cervical spine x-ray, CT and MRI preoperatively and postoperatively. The patients were followed up at 1 month, 3 months, 6 months, and 12 months after operation, and once a year thereafter. Clinical outcomes were evaluated during follow-up, and performed x-ray, CT or MRI examinations according to the patient's condition. At last follow-up, the clinical outcomes were evaluated, and x-ray, CT and MRI examinations were performed concurrently. Clinical and radiological outcomes at the last follow-up were used for analysis.

The distance between the anteroposterior diameter of the dura of C2/3 was assessed on T2-weighted MR cross-sectional images of the cervical spine (**Figure 4**). The C2–C7 cervical curvature index (CCI) at the last follow-up and preoperative CCI were recorded by cervical lateral x-ray to calculate the changes in lordosis. The ossification type of the posterior longitudinal ligament of the cervical spine was recorded on the lateral CT of the cervical spine. Three independent spinal surgeons, who were not involved in the study, performed radiological measurements, and the average values of all observers were used in the present study.

Neurological function was assessed using the Japanese orthopedic association (JOA) score. The neurological recovery rate (RR) was calculated as follows: recovery rate (%) = (final JOA score—preoperative JOA score)/(17—preoperative JOA score) × 100. The visual analogue scale (VAS) score was used to evaluate axial pain in the posterior cervical region or in the suprascapular region. The functional status of the cervical spine was assessed using the neck disability index (NDI). Three independent spinal surgeons, who were not involved in the study, performed the assessments, and the average values of all observers were used in the present study. Patients' complications, such as cerebrospinal fluid leakage, infection, nerve root palsy, axial neck pain, neurological deterioration, and implant failure were recorded.

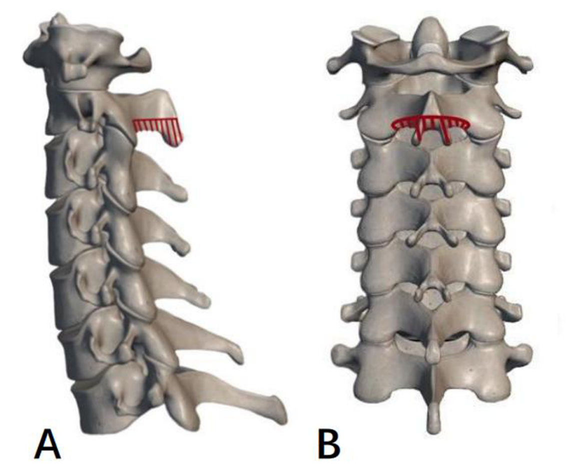

FIGURE 2
Schematic diagram of C2 partial laminectomy (C2-PL). (A,B) The red dotted area is the part of the lamina and spinous process to be resected.

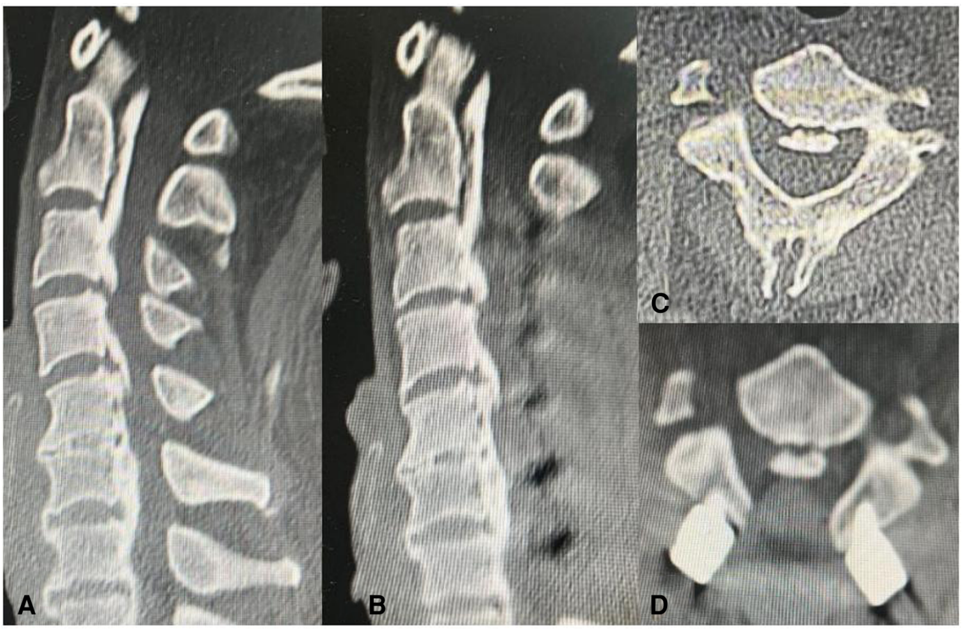

FIGURE 3
CT scans showing the extent of bone removed by C2 partial laminectomy (C2-PL). (A,C) showing the CT image of the cervical spine before the surgery. (B,D) showing the CT image of the cervical spine after the surgery.

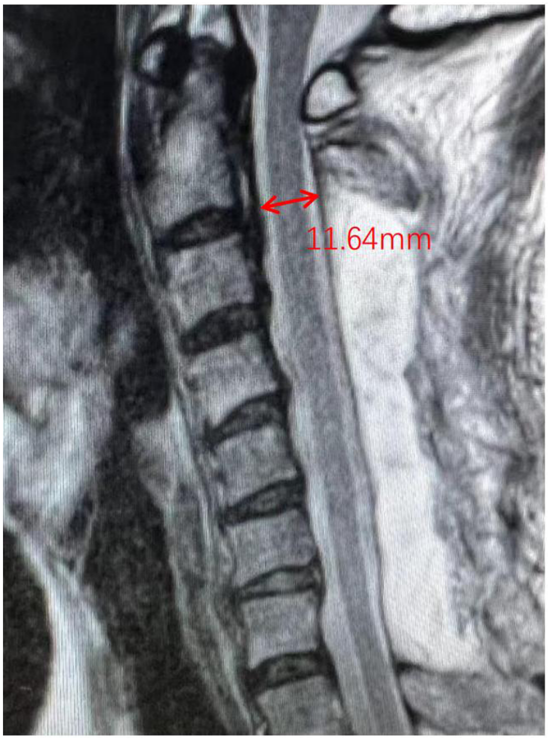

FIGURE 4
Schematic diagram of C2/3 dura width. The width of C2/3 on MRI scan was evaluated. The dura width in schematic diagram was 11.64 mm.

Statistical analysis

Continuous data are presented as means ± standard deviations (SD), while categorical data are shown as absolute frequencies. The Wilk-Shapiro test was used to assess normality of data distribution. The unpaired *t*-test or Mann–Whitney *U* test were used to analyze parametric and nonparametric continuous data, respectively. The Chi-square test was used to analyze categorical data. Paired *t*-test or Wilcoxon test were used for intra-group comparisons of parametric and nonparametric continuous data, respectively. Data were analyzed using SPSS 25.0 software (IBM Corp., Armonk, NY, USA). $P < 0.05$ was considered statistically significant.

Results

32 patients were involved in this study, including 26 men and 6 women. Patients' age ranged between 45 and 72 years, with a mean age of 57.5 ± 8.4 years old. A total of 29 patients (90.63%) had ossified C2 segment, 3 patients (9.38%) had ossified C1 segment, 10 (31.25%) patients had mixed ossification, 18 (56.25%) patients had continuous ossification, and 4 (12.5%) patients had segmental ossification. All patients were followed up for 2–8 years, with an average of 3.25 years. There were 31 patients with comorbidities, including 13 patients with heart disease, 20 patients with hypertension, 10 patients with cerebrovascular disease, 2 patients with diabetes mellitus, and 2 patients with osteoporosis.

There was no significant difference in demographic data between the two groups of patients (Table 1). As shown in Table 2, there were no significant differences in the type of the OPLL, preoperative C2/3 dura width, and preoperative CCI between the two groups. At the last follow-up, the width of the dura at C2/3 in both groups significantly increased compared with that before surgery (C2-DOM group: 12.6 ± 1.5 mm vs. 7.9 ± 1.9 mm, $P < 0.001$; C2-PL group: 13.5 ± 0.9 mm vs. 7.3 ± 1.5 mm, $P < 0.001$), and the width of the dura at C2/3 in the C2-PL group was significantly larger than that in the C2-DOM group (13.5 ± 0.9 mm vs. 12.6 ± 1.5 mm, $P < 0.001$). At the last follow-up, the CCI value was 17.9 ± 9.4% in C2-DOM group and 15.8 ± 5.2% in C2-PL group with no significant differences ($P = 0.598$).

As shown in Table 3, functional outcomes in both groups significantly improved, and there was no significant difference in the preoperative JOA score, NDI score, and VAS score, between the two groups. At the last follow-up, significant improvements in JOA score, NDI score and VAS score were observed in the two groups. There was no significant difference in the JOA score and NDI score between the two groups at the final follow-up. The VAS scores in both groups were increased at the last follow-up (C2-DOM group: 24.6 ± 1.6; C2-PL group: 35.9 ± 1.5), however, the VAS score of C2-DOM group was significantly less than that in C2-PL group ($P < 0.001$).

There was 1 patient in the C2-DOM group who experienced C5 palsy after surgery ($P = 1$), and it was resolved after conservative treatment. In addition, 1 patient in the C2-DOM group and 3 patients in the C2-PL group experienced sustained axial pain after surgery ($P = 0.600$), and they were not significantly improved at the last follow-up. Besides, 1 patient in the C2-DOM group had cerebrospinal fluid leakage (CSF), which resolved at 6 days after surgery when the drainage tube was removed and the incision was sutured

TABLE 1 Comparison of patient characteristics between C2-DOM group and C2-PL group.

	C2-DOM group (*n* = 16)	C2-PL group (*n* = 16)	*P*-value
Age (years)	57.9 ± 8.7	57.2 ± 8.3	0.812
Gender (male/female)	13/3	13/3	1
Body Mass Index (Kg/m^2)	30.5 ± 5.2	26.9 ± 4.0	0.112
Follow-up (months)	37.9 ± 14.8	40.3 ± 13.9	0.634
Operation time (minutes)	194.7 ± 83.2	198.4 ± 68.9	0.89
Blood loss (ml)	562.5 ± 387.9	443.8 ± 222.8	0.42

Values are expressed as mean ± standard deviation. C2-DOM group = C2 dome-like laminectomy group. C2-PL group = C2 partial laminectomy group.

TABLE 2 Comparison of radiological measurement between C2-DOM group and C2-PL group.

	C2-DOM group (*n* = 16)	C2-PL group (*n* = 16)	*P*-value
Type of OPLL			0.497
Local	0	0	
Segmental	1	3	
Continuous	9	9	
Mixed	6	4	
Dura width at C2/3 (mm)			
Preoperative	7.9 ± 1.9	7.3 ± 1.5	0.366
Last follow-up	12.6 ± 1.5	13.5 ± 0.9	0.043
P-value	<0.001	<0.001	
CCI (%)			
Preoperative	21.5 ± 7.8	18.5 ± 8.0	0.293
Last follow-up	17.9 ± 9.4	15.8 ± 5.2	0.598
P-value	0.071	0.143	

Values are expressed as mean ± standard deviation. C2-DOM group = C2 dome-like laminectomy group. C2-PL group = C2 partial laminectomy group. OPLL, ossification of posterior longitudinal ligament; CCI, cervical curvature index.

TABLE 3 Comparison of clinical outcomes between C2-DOM group and C2-PL group.

	C2-DOM group (*n* = 16)	C2-PL group (*n* = 16)	*P*-value
JOA			
Preoperative	9.3 ± 2.0	10.2 ± 2.0	0.225
Last follow-up	14.8 ± 1.2	14.7 ± 2.4	0.530
P-value	<0.001	<0.001	
RR (%)	72.2	64	0.676
NDI (%)			
Preoperative	25.8 ± 10.7	24.8 ± 12.6	0.808
Last follow-up	11.7 ± 4.6	16.0 ± 6.3	0.692
P-value	<0.001	0.020	
VAS			
Preoperative	22.3 ± 1.5	23.1 ± 2.7	0.348
Last follow-up	24.6 ± 1.6	35.9 ± 1.5	<0.001
P-Value	<0.001	<0.001	
Postoperative Complications [number of patients (percentage)]			
C5 nerve root palsy	1(6.3%)	0	1
Axial neck pain	1 (6.3%)	3 (18.8%)	0.600
CSF leakage	1 (6.3%)	0	1
Spinal cord injury	0	1 (6.3%)	1
Infection	0	0	
Implant failure	0	0	
Hematoma	0	0	

Values are expressed as mean ± standard deviation. C2-DOM group = C2 dome-like laminectomy group. C2-PL group = C2 partial laminectomy group. JOA, Japanese orthopedic association; RR, recovery rate; VAS, visual analog scale; NDI, neck disability index; CSF, cerebrospinal fluid leakage.

under local anesthesia. Moreover, 1 case in the C2-PL group was found with deterioration of bilateral limb muscle strength after recovery from anesthesia. Methylprednisolone was given as a bolus dose of 30 mg/kg in 15 min, followed by a pause of 45 min and a subsequent continuous infusion of 5.4 mg/kg/hour for 23 h. However, muscle strength did not improve, being grade 2/5 according to manual muscle test (MMT) at the last follow-up. No significant differences were found regarding complication rates between the two groups (Table 3). No patients in either group experienced infection, hematoma, implant failure, or other complications after surgery.

Discussion

The surgical treatment of cervical OPLL includes anterior surgery, posterior surgery, and combination of anterior and posterior surgery. Although anterior surgery can achieve the objective of direct and sufficient decompression (10, 11), the risk of anterior surgery is higher (12, 13).

Kong et al. (14) concluded that the space available at the level cephalad to the stenotic segment is an important predictor of cord postoperative shift. Therefore, when MRI shows compression above the C2/3 intervertebral disc, only the decompression of the segment below C3 may result in the limited posterior translation of the spinal cord and insufficient decompression above the C2/3, which may affect the recovery of neurological function. Therefore, decompression above the C2/3 segment is necessary. Some researchers have also used anterior surgery to decompress the upper cervical spine. Chen et al. (15) reported a case of anterior controllable anti-displacement and fusion (ACAF), and achieved satisfactory recovery after surgery. The surgical technique is complicated, and the extent of surgical decompression cannot be directly observed intraoperatively. Therefore, the posterior approach was selected in the present study.

As for surgical decompression at the C2 level, Takeshita (16) demonstrated that compared with C3–C7 open-door laminoplasty, additional C2 open-door laminoplasty would disrupt the overall balance of the cervical spine and lead to cervical instability. Therefore, no patient underwent C2 laminoplasty in this study. In 1989, Matsuzaki (7) proposed C2 dome-shaped laminoplasty for the treatment of OPLL involving C2, and achieved satisfactory clinical results. Next, in 2016, Japanese scholars reported this lamina-sparing C2 dome-shaped decompression surgical method. While some researchers (9) pointed out that the C2-DOM is complicated, and measuring and reproducing the "dome" size and shape is challenging, C2-PL may also achieve satisfactory clinical results. However, a few studies compared the efficacy of C2-DOM and C2-PL in the treatment of upper cervical OPLL.

In our study, there was no significant difference in the preoperative NDI score, VAS score, and the recovery of neurological function between the two groups. The VAS scores in the C2-DOM group were significantly better than those in the C2-PL group after surgery (**Table 3**). Research suggested that disruption of the C2 spinous process, the attachment of the semispinalis cervicalis, and the semispinalis capitis muscle, as well as surgery involving the C7 segment, may cause or aggravate postoperative neck pain (17, 18). Shunsuke et al. found that the decrease in the strength of the deep extensor muscles of the neck after surgery was resulted in an imbalance of the extensor and flexor muscles at the cervical spine, which was highly correlated with axial symptoms (19). C2-PL removes a part of the lamina and C2 spinous process, disrupting the attachment of muscles and ligaments, while C2-DOM only partially removes the ventral structure of the C2 lamina and preserves the C2 spinous process. Through C2-DOM, not only the C2 segment is fully decompressed and the backward shift distance of the spinal cord increases, but also decreases the surgical damage to posterior neck muscles reducing the incidence of postoperative neck pain. According to the results of the present study, C2-DOM is superior to C2-PL in terms of postoperative axial symptoms.

In the present study, the CCI was measured to evaluate cervical lordosis in the two groups. Excessive destruction of posterior facet joint and muscle ligament structure, especially muscle attachment at C2 segment, was reported to be associated with postoperative cervical kyphosis and deterioration of neurological function (20). Biomechanical and clinical studies have shown that preservation of the semispinalis muscle could reduce the incidence of cervical kyphosis and stabilize the cervical spine (9). Liu et al. (21) reported that as the majority of patients had continuous OPLL located behind the C2 and C3 vertebral bodies, the lordotic effect might reduce the incidence of segmental kyphosis after surgery. Therefore, they suspected that C2 single-door laminoplasty could not increase the incidence of postoperative cervical kyphosis. Yu et al. (22) showed that there was no significant difference in the results of CCI at the last follow-up between the two groups of patients who underwent C2 single-door surgery or C2-DOM. In the present study, postoperative CCI in the C2-PL group was not significantly different from that in the C2-DOM group with less damage to the C2 muscle attachment, which could be related to the fact that the majority of patients in the C2-PL groups had continuous OPLL located behind the C2 and C3 vertebral bodies, and bony structure maintained the cervical lordosis, which could also be attributed to the small sample size of this study.

The postoperative dura width at C2/3 in the C2-DOM group was 12.6 mm, and the postoperative C2/3 dura width in the C2-PL group was 13.5 mm. C2-PL achieved decompression of the dorsal side of the C2 spinal cord by partially removing the lamina and C2 spinous process. The C2-DOM could retain the original shape of the C2 vertebral body *via* partially removing the bone and adhering ligament tissue on the ventral side of the C2 lamina. Therefore, the decompression of the C2 segment in the C2-PL is more thorough than the dome-like decompression of the C2 laminectomy. When the ossification above the C2/3 occupies a large area of the spinal canal, C2-PL can achieve a more adequate decompression. Overall, C2-DOM led to less postoperative axial symptoms in patients, and C2-PL was more efficacious in expanding the effective spinal cord space. C2-PL can achieve more adequate decompression when the ossification above the C2/3 level occupies a large space in the spinal canal.

This study has some limitations. First, the number of patients included in this study was small due to the low incidence of upper OPLL. Second, the follow-up period was short, with an average of 39 months, thus, the long-term clinical efficacy needs to be further evaluated. Furthermore, the small sample size and short follow-up time might lead to inaccurate radiological measurements, especially for the incidence of cervical kyphosis. Finally, this was a retrospective study, and there might be retrospective bias in data collection. Therefore, further multicenter, prospective, randomized controlled study should be conducted for further validation.

Conclusions

Both C2-DOM and C2-PL can treat patients with upper OPLL and achieve effective decompression. C2-DOM has less damage and lower postoperative neck pain, while C2-PL possesses more advantages in terms of expanding the spinal canal, and the risk of cervical kyphosis is comparable to that of C2-DOM.

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

The studies involving human participants were reviewed and approved by the Third Affliated Hospital of Hebei Medical University. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

Author contributions

DM and XG: are responsible for the integrity and authenticity of this work, conception and design, and writing and critical revision of the article. ZZ and HW: literature research. DM and XG: data extraction. DM and XG: data analysis. WD and DY: give guidance and advice. 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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A single-arm retrospective study of the clinical efficacy of unilateral biportal endoscopic transforaminal lumbar interbody fusion for lumbar spinal stenosis

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Objective: The purpose of this study was to investigate the clinical efficacy of unilateral biportal endoscopic transforaminal lumbar interbody fusion (UBE-TLIF) for lumbar spinal stenosis (LSS).

Methods: Patients who underwent UBE-TLIF due to single-segment LSS between August 2019 and July 2021 were retrospectively included in the study. Clinical outcomes evaluated include operative time, estimated blood loss (including postoperative drainage), time to ambulation, postoperative hospital stay, complications, visual analog scale (VAS) scores of low back pain and leg pain, Japanese Orthopaedic Association (JOA) score, Oswestry disability index (ODI), and modified Macnab criteria. Interbody bony fusion at the index level was assessed using Bridwell grading criteria.

Results: A total of 73 patients (29 males and 44 females) were enrolled in this study. All surgeries were successfully performed without intraoperative conversion to open surgery. Magnetic resonance imaging (MRI) revealed optimal direct neural decompression after UBE-TLIF. The mean operative time was 150.89 ± 15.58 min. The mean estimated blood loss was 126.03 ± 17.85 ml (postoperative drainage was 34.84 ± 8.31 ml). Time to ambulation was 2.0 ± 0.75 days after the procedure. Postoperatively, the mean hospital stay was 5.96 ± 1.38 days. VAS scores of low back pain and leg pain, JOA, and ODI were significantly improved postoperatively compared with those before the operation, and differences were statistically significant ($P < 0.05$). Excellent and good outcomes were reported by 87.67% of patients according to the modified Macnab criteria at the final follow-up. A total of nine perioperative complications occurred, with an incidence of 12.33%. X-ray or computerized tomography (CT) 6 months after the procedure showed that 37 cases (50.68%) presented with segmental fusion, 30 cases (41.10%) showed incomplete fusion, and 6 cases (8.22%) showed no signs of fusion. However, bony fusion was achieved in all cases at the final follow-up.

Conclusions: UBE-TLIF for LSS has the advantages of less surgical invasiveness and fast postoperative recovery.

KEYWORDS

lumbar spinal stenosis, unilateral biportal endoscopy technique, lumbar interbody fusion, spinal endoscopic surgery, minimally invasive

Introduction

Lumbar spinal stenosis (LSS) is a disease caused by the compression of the dural sac and nerve root due to various factors such as hypertrophy of the ligamentum flavum (LF), facet joint hypertrophy, disc herniation, and spondylolisthesis, resulting in low back pain, leg pain with or without numbness, intermittent claudication, and bladder and bowel dysfunction, in which intermittent neurogenic claudication is the main feature. Degenerative LSS affects most commonly the elderly (1, 2). Conservative treatment is preferred for symptomatic LSS, while surgery may be considered for patients with severe radicular pain and walking disability who have failed to respond to conservative treatments, which accounts for approximately 8%–11% of degenerative lumbar spinal diseases that require surgical procedures (2–4). Traditional surgical approaches include open laminotomy decompression, foraminotomy, discectomy, and fusion (5–7). Conventional open lumbar decompression has a long history and has the advantages of adequate decompression and clear visualization of neural structures, while surgical invasiveness and extensive stripping of paraspinal muscles and soft tissues may lead to a series of problems such as postoperative low back pain, spinal instability, and prolonged hospital stay and time to return to normal life after the operation (8, 9). To address many of these shortcomings, innovative and less demolishing surgical techniques are being developed and investigated.

Minimally invasive spine surgery has become increasingly popular in recent years. Unilateral biportal endoscopy (UBE) was proposed by Heo in 2017 to treat degenerative lumbar spinal diseases with less damage to the paraspinal muscles (10). Unilateral biportal endoscopic transforaminal lumbar interbody fusion (UBE-TLIF) based on this technique is a newly emerging minimally invasive fusion surgery, and some studies have reported excellent outcomes in the treatment of LSS (10–13). Despite its recent introduction, the use of UBE is growing, thus requiring more clinical research to carefully evaluate outcomes related to this innovative technique. Consequently, this study was conducted to evaluate the clinical efficacy of UBE-TLIF by retrospectively analyzing clinical and radiological outcomes in a cohort of patients affected by LSS.

Materials and methods

This was a single-arm retrospective study. The study protocol was approved by the Ethics Committee of the First Affiliated Hospital of Xinjiang Medical University and performed according to the Declaration of Helsinki. A total of 73 patients (29 men and 44 women) diagnosed with LSS and treated with UBE-TLIF between August 2019 and July 2021 were included in the study. All patients were informed of all potential risks of the surgery and signed written consent before the procedure.

The inclusion criteria are as follows: (1) definite diagnosis of LSS (central stenosis, lateral recess stenosis, and foraminal stenosis) with or without segmental instability (anterior translation [>3 mm], and/or increasing segmental sagittal motion [>15°]), with or without low-grade lumbar spondylolisthesis (grade ≤ 2) on flexion/extension radiographs, including degenerative spondylolisthesis and isthmic spondylolisthesis; (2) patients with neurogenic claudication, pain, and numbness in the lower limbs, with or without low back pain, who have failed for more than 6 months of conservative treatment; (3) UBE-TLIF surgery; and (4) postoperative follow-up time ≥12 months. The exclusion criteria are as follows: (1) previous posterior decompression at the index level; (2) other concomitant spinal diseases (e.g., spinal infections, spinal tumors, and spinal trauma); (3) high-grade (Meyerding grade 3 or 4) isthmic spondylolisthesis and degenerative spondylolisthesis; (4) LSS involving two or more segments; and (5) presence of surgical contraindications.

Surgical methods

All procedures were performed by the same surgical team. The patient was positioned prone on the operating table after achieving satisfactory general anesthesia. The target segment was identified, and portals were marked under C-arm fluoroscopy guidance, followed by skin asepsis and sterile draping. Two K-wires were inserted into the marked portals under fluoroscopy to confirm the disc space located at the target segment. Two longitudinal incisions of approximately 1.5 cm were made for viewing and working portals to introduce an arthroscope and surgical instruments, respectively. Two incisions were located 1 cm above and 1 cm below the center, where the two K-wires' junction points were located and placed close to the outer side of the pedicle. In left-sided approaches, the cranial portal was used as the viewing portal and the caudal portal was used as the working portal, while the opposite order was followed in right-sided approaches. Serial dilators and laminar dissectors were inserted through the portals and placed in direct contact with the bone, and the precise location was confirmed by fluoroscopy (**Figures 1A,B**). After soft tissue debridement with an arthroscopic shaver and careful hemostasis, an osteotome or a K-wire was inserted in the facet joint space or in contact with the bone surface, and the target segment location was again confirmed by fluoroscopy (**Figure 1C**). Ipsilateral laminectomy and facetectomy were performed first. Osteotomes, Kerrison punches, and high-speed burrs were used to remove the inferior articular process (IAP) and the inferior margin of the superior lamina to expose the origin of the LF, the superior margin of the inferior lamina to reveal the end of the LF, and then the apical and medial margins of the superior articular process (SAP). Subsequently, contralateral decompression was performed. Local autologous bone obtained during the procedure was saved for later use as an interbody bone graft. In case of insufficient autologous bone, artificial or allogenic bone grafts were used. The LF overlying the dura and nerve roots was removed following ipsilateral and contralateral decompression, and facetectomy was completed.

Subsequently, ipsilateral and contralateral nerve roots were explored to ensure adequate decompression (**Figures 1D,E**). Annulotomy was performed with a sharp knife following the dura and nerve root being protected and then discectomy with tools. The arthroscope was introduced into the intervertebral space to monitor the preparation of the endplate (**Figure 1F**), the cartilaginous endplate was removed completely with a curette, and the subchondral bone was exposed until the wound had blood ooze. A cage trial implant was inserted into the disc space to restore the intervertebral height while avoiding subchondral bone injury and to determine the size of the real cage. A special cannula was used to fill the anterior part of the disc space with local autogenous bone and artificial bone owing to the concern of bone loss caused by continuous irrigation. The cage was carefully

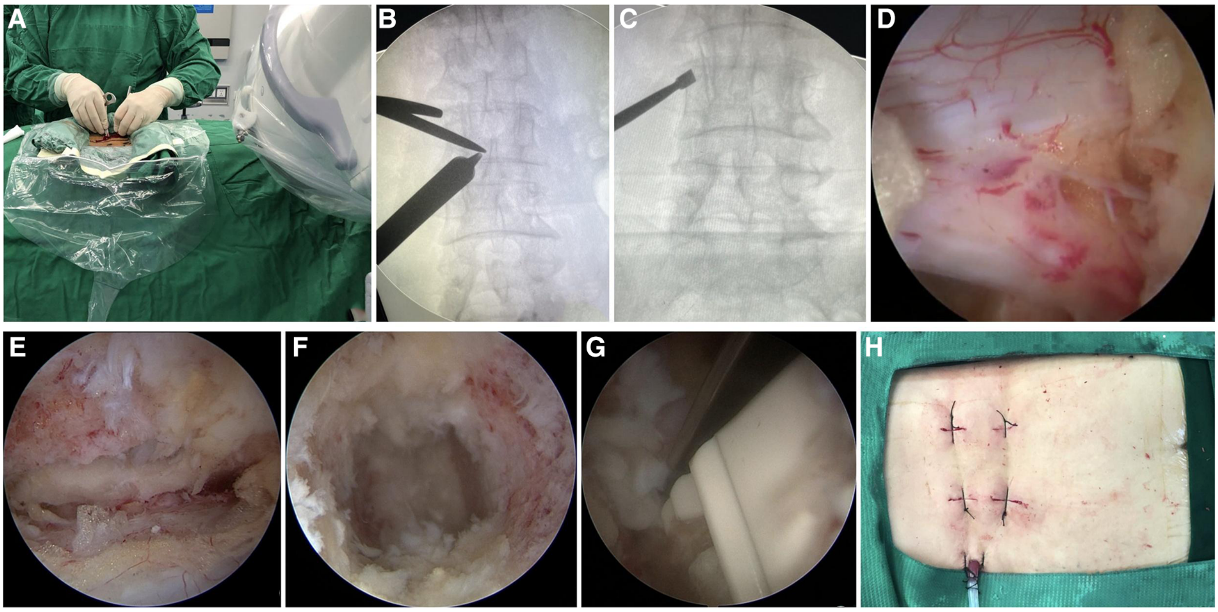

FIGURE 1
Intraoperative images of UBE-TLIF. (A) Operator creates two portals. (B) Location of the junction point of the serial dilators and the lamina dissector was confirmed by C-arm fluoroscopy. (C) Target segment was confirmed by C-arm fluoroscopy. (D,E) Endoscopic images of the dura, ipsilateral traversing root, and contralateral traversing root. (F) Endoscopic showed the intervertebral space with the cartilaginous endplate completely removed. (G) Cage was inserted under endoscope guidance. (H) Photo of the incision after completion of the operation.

inserted in the intervertebral disc space under arthroscopic observation to avoid injury to the dura and nerve roots (Figure 1G). Eventually, the adequateness of cage size and position was demonstrated by fluoroscopy. Subsequently, the arthroscope and endoscopic instruments were withdrawn, and ipsilateral pedicle screws were implanted via the viewing and working portals. Contralateral pedicle screws were placed percutaneously using conventional skin incisions. A surgical drain was positioned to drain small bony debris and prevent epidural hematoma, and incisions were sutured (Figure 1H).

Postoperative management

Intravenous antibiotic prophylaxis was administered for 24 h postoperatively, and nonsteroidal anti-inflammatory drugs (NSAIDs) were used to reduce pain. The drain tube was removed when the drain flow was <30 ml/24 h. The patients were allowed to walk with a brace 1 day postoperatively, and brace protection continued for 2–3 months. X-ray (Figures 2B,G) and computerized tomography (CT) (Figures 2D,I) were performed on all patients before discharge to evaluate the location of the graft and instrumentation, and adequateness and extent of decompression were assessed by sagittal and axial magnetic resonance imaging (MRI) (Figures 2F,K).

Outcome measures

All patients were evaluated clinically and by x-ray, CT, and MRI (Figures 2A,C,E,H,J). Operative time, estimated blood loss (including postoperative drainage), time to ambulation, postoperative hospital stay, and complications were recorded and documented. Visual analog scale (VAS) scores of low back pain and leg pain, Japanese Orthopaedic Association (JOA) scores, and the values of Oswestry disability index (ODI) preoperatively and during the follow-up period (1 day, 1 month, 3 months, and 6 months after surgery, and the last follow-up) were recorded. Modified Macnab (14) criteria were appraised at the last follow-up. Intervertebral bony fusion was assessed using Bridwell grading criteria (15). When there was uncertainty in x-ray, further evaluation was done by CT.

Statistical analysis

The data were statistically analyzed using SPSS 26.0 software. The continuous data were expressed as the mean ± standard deviation (SD), and significant differences in repeated-measures data (VAS, JOA, and ODI) were determined using repeated-measures analysis of variance. $P < 0.05$ was considered to be statistically significant.

Results

A total of 73 patients (29 men and 44 women, 60.78 ± 7.29 years) that met the criteria were included in our study. All patients were followed for at least 12 months, and the average follow-up time was 17.92 ± 3.22 months. A total of 10 patients had central stenosis, 10 patients had central stenosis with lateral recess stenosis, 11 patients had central stenosis with concomitant foraminal stenosis, 16 patients had central stenosis with segmental

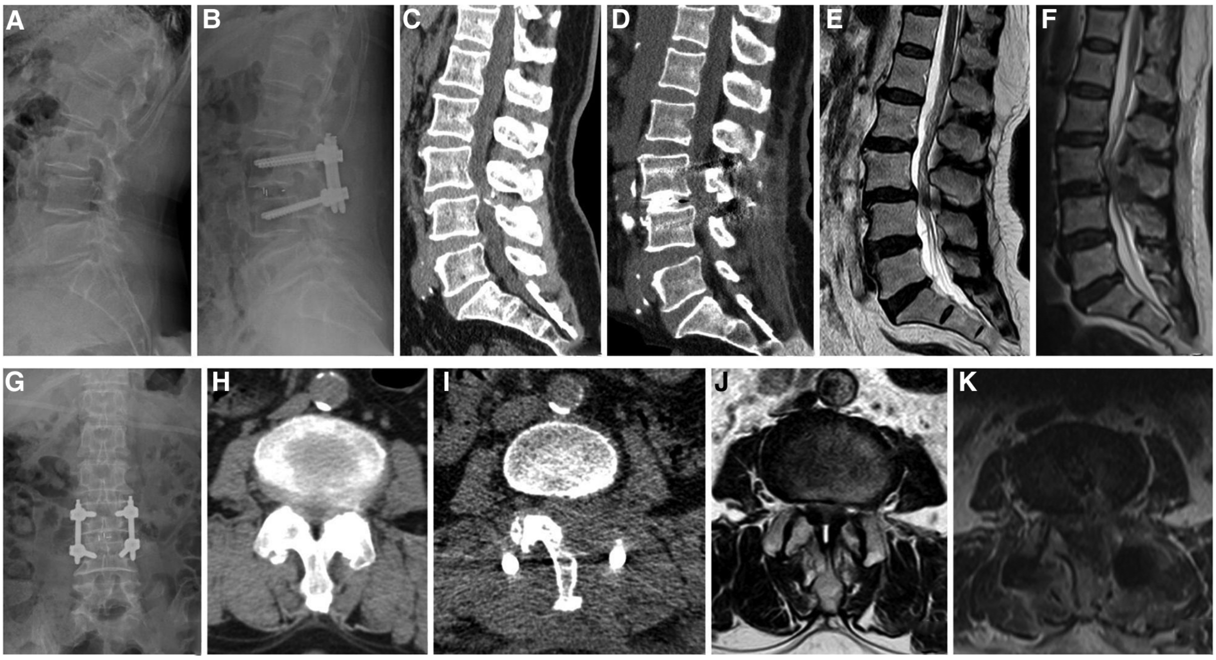

FIGURE 2
A 62-year-old female patient, whose complaints were low back pain since 3 years, lower limbs numbness, and intermittent claudication since 5 months. (A,C, E) Preoperative lateral radiographs, sagittal CT, and MRI showing instability of the L3 vertebral body, L3–4 spinal stenosis, and ossification of the posterior ligamentum flavum. (H,J) Preoperative axial CT and MRI showing significant spinal stenosis in L3–4. (B,G) Postoperative anteroposterior and lateral radiographs showing a good position of the instrumentation and the cage and improved segmental instability. (D) Postoperative sagittal CT showing that adequate bone was grafted. (F) Postoperative sagittal MRI showing that spinal stenosis was improved. (I) Postoperative axial CT showing unilateral laminectomy bilateral decompression. (K) Postoperative axial MRI showing sufficient decompression and a good position of the cage.

instability, 16 patients had LSS with degenerative spondylolisthesis, and 10 patients had LSS with isthmic spondylolisthesis. The operative levels ranged from L2–3 to L5–S1: L2–3 in 7 patients, L3–4 in 15 patients, L4–5 in 32 patients, and L5–S1 in 19 patients (Table 1).

All patients completed the procedure successfully without intraoperative conversion to open surgery. The mean operative time was 150.89 ± 15.58 min. The mean estimated blood loss was 126.03 ± 17.85 ml (postoperative drainage was 34.84 ± 8.31 ml). The time to ambulation was 2.0 ± 0.75 days after the procedure. The mean postoperative hospital stay was 5.96 ± 1.38 days (Table 2). Preoperative VAS scores improved significantly after the surgery: the mean VAS scores of low back pain and leg pain were 5.23 ± 1.67 and 5.62 ± 2.25, respectively, before surgery, which improved to 3.03 ± 1.25 and 3.62 ± 1.90 the next day after surgery ($P < 0.05$). The VAS scores of low back pain and leg pain were 2.10 ± 1.23 and 2.58 ± 1.50, respectively, 1 month after the operation, which improved significantly over the corresponding preoperative values ($P < 0.05$). The VAS scores of low back pain and leg pain were 1.53 ± 0.96 and 1.52 ± 1.0, respectively, 3 months after the operation, which improved significantly over the corresponding preoperative values ($P < 0.05$). The VAS scores of low back pain and leg pain were 1.23 ± 0.94 and 1.01 ± 0.66, respectively, 6 months after the operation, which improved significantly over the corresponding preoperative values ($P < 0.05$). The final VAS scores of low back pain and leg pain were 0.96 ± 0.77 and 0.93 ± 0.75, respectively ($P < 0.05$). Postoperative JOA scores significantly improved compared to preoperative scores: the mean JOA score was 10.75 ± 2.23. The 1-month JOA score was 19.30 ± 2.18 ($P < 0.05$). The 3-month JOA score was 21.07 ± 1.80 ($P < 0.05$). The 6-month JOA score was 23.12 ± 1.76 ($P < 0.05$). The final JOA score was 27.01 ± 1.31 ($P < 0.05$). Moreover, the preoperative ODI score (65.73 ± 8.29) also improved significantly at the follow-up ($P < 0.05$). The 1-month ODI score was 45.66 ± 8.22 ($P < 0.05$). The 3-month ODI score was 35.76 ± 7.93 ($P < 0.05$). The 6-month ODI score was 22.81 ± 3.60 ($P < 0.05$). The final ODI score was 9.67 ± 2.42 ($P < 0.05$) (Table 3). Based on the modified Macnab criteria at the final follow-up, the clinical outcomes were excellent in 50 (68.49%) patients, 14 (19.18%) patients had good clinical outcomes, 9 (12.33%) patients had fair clinical outcomes, and none of the patients showed poor outcomes. In total, 87.67% showed excellent to good outcomes, and 12.33% showed fair outcomes (Table 4). X-ray or computerized tomography (CT) (Figures 3A,B) 6 months after the procedure showed that 37 cases (50.68%) presented with segmental fusion, 30 cases (41.10%) showed incomplete fusion, and 6 cases (8.22%) showed no signs of fusion. However, bony fusion was achieved in all cases at the final follow-up (Figures 3C,D). No loosening or fracture of the internal fixation occurred in all patients.

We observed nine cases of perioperative complications: three patients with postoperative epidural hematoma, two patients with a dural tear, two patients with transient pain in the buttocks, one patient with temporary dysesthesia, and one patient with transient muscle paralysis of both lower limbs, in which the incidence of complications was 12.33% (Table 5). None of these patients underwent revision surgery, and their complications recovered after conservative treatment. No infection was observed in our patients.

TABLE 1 Demographic and surgical characteristics of included patients.

Variables	Value
Age (years)	
Mean	60.78 ± 7.29
Range	45–75
Gender	
Male	29
Female	44
Follow-up times (months)	17.92 ± 3.22
Diagnosis	
Central stenosis with segmental instability	16
LSS with DS	16
Central stenosis with concomitant foraminal stenosis	11
Central stenosis with lateral recess stenosis	10
Central stenosis	10
LSS with IS	10
Spondylolisthesis	
DS	
Grade 1	13
Grade 2	3
IS	
Grade 1	6
Grade 2	4
Level treated	
L2–3	7
L3–4	15
L4–5	32
L5–S1	19
Approach	
Ipsilateral decompression	43
Bilateral decompression	30
Approaching side	
Left	45
Right	28

Values are presented as the number of patients unless stated otherwise.
DS, degenerative spondylolisthesis; IS, isthmic spondylolisthesis; LSS, lumbar spinal stenosis.

TABLE 2 Results related to UBE-TLIF.

Variable	Value
Operative time (min)	150.89 ± 15.58
Estimated blood loss (ml)	126.03 ± 17.85
Postoperative drainage (ml)	34.84 ± 8.31
Time to ambulation (days)	2.0 ± 0.75
Postoperative hospitalization time (days)	5.96 ± 1.38

TABLE 3 Clinical outcomes (VAS, JOA, and ODI) pre- and post-surgery.

Date	VAS score of low back pain	VAS score of leg pain	JOA score	ODI score (%)
Preoperative	5.23 ± 1.67	5.62 ± 2.25	10.75 ± 2.23	65.73 ± 8.29
Postoperative				
1 day	3.03 ± 1.25[a]	3.62 ± 1.90[a]	-	-
1 month	2.10 ± 1.23[a]	2.58 ± 1.50[a]	19.30 ± 2.18[a]	45.66 ± 8.22[a]
3 months	1.53 ± 0.96[a]	1.52 ± 1.0[a]	21.07 ± 1.80[a]	35.76 ± 7.93[a]
6 months	1.23 ± 0.94[a]	1.01 ± 0.66[a]	23.12 ± 1.76[a]	22.81 ± 3.60[a]
Final follow-up	0.96 ± 0.77[a]	0.93 ± 0.75[a]	27.01 ± 1.31[a]	9.67 ± 2.42[a]
p-Value	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$

VAS, visual analog scale; JOA, Japanese Orthopaedic Association; ODI, Oswestry disability index.
[a]Significantly different from the preoperative value ($P < 0.05$).

TABLE 4 Clinical outcome of surgery based on modified Macnab criteria.

Classification	Frequency (%)
Excellent	50 (68.49)
Good	14 (19.18)
Fair	9 (12.33)
Poor	–

Discussion

LSS is a common degenerative lumbar spinal disease in the elderly, whose incidence rate is accruing every year, and patients' expectations from surgery are also improving. Although traditional open transforaminal lumbar interbody fusion (TLIF) and posterior lumbar interbody fusion (PLIF) can be effective treatments for LSS by directly decompressing the spinal canal through the posterior approach, disruption of the posterior muscles and ligamentous structures may lead to complications such as postoperative low back pain and muscle atrophy (16, 17). Therefore, more time may be required for functional recovery after conventional open fusion surgery, resulting in relatively longer postoperative hospital stays and higher costs associated with postoperative care. Consequently, minimally invasive fusion techniques such as oblique lumbar interbody fusion, percutaneous endoscopic lumbar interbody fusion, and minimally invasive transforaminal lumbar interbody fusion (MI-TLIF) have been developed to minimize the procedure-related injuries of posterior muscles and ligamentous structures (16, 18–20).

The UBE technique has been recently introduced with different applications, including decompression and interbody fusion (11, 21–29). It is based on using two independent portals (viewing and working) requiring two small incisions. Lately, UBE to perform

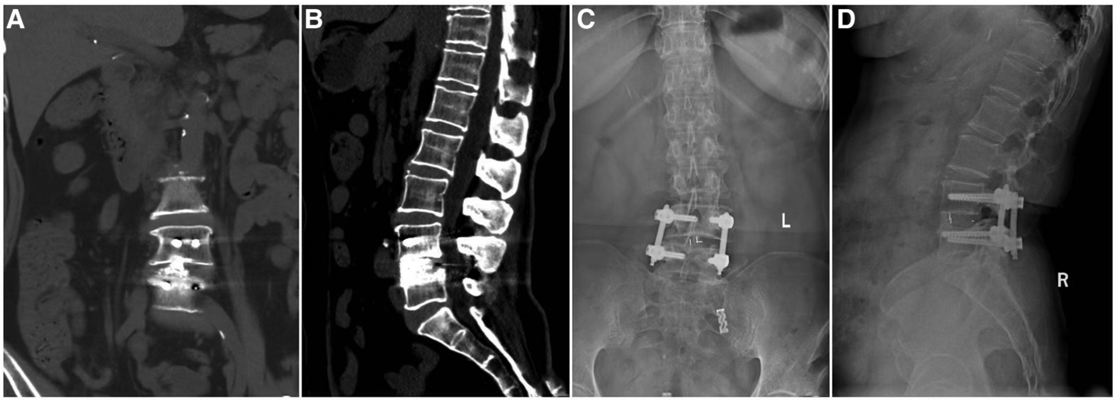

FIGURE 3
Imaging findings during follow-up of a patient who underwent UBE-TLIF. (A,B) Coronal and sagittal CT showing that the cage was well positioned and high-density bone fusion between vertebral bodies 6 months after the operation. (C,D) 13-month postoperative x-ray showing bony fusion and that the instrumentation was in a good position.

TABLE 5 Complications of included patients.

Complication	Value	Incidence (%)
Postoperative epidural hematoma	3	4.11
Dural tear	2	2.74
Transient pain in the buttocks	2	2.74
Temporary dysesthesia	1	1.37
Transient muscle paralysis of both lower limbs	1	1.37
Total	9	12.33

TLIF (here defined as UBE-TLIF) has been described (10, 11). This technique has some advantages such as a clear view, wide working space, and operative freedom, additionally allowing the use of conventional spinal surgical tools for decompression, which combines the features of endoscopic surgery with those of traditional open surgery and truly embodies the minimally invasive concept. It does not require a tubular retractor during the procedure, similar to traditional open spine surgery, and the extent of intraoperative decompression can be evaluated as needed. It is less disruptive to normal bony structures than conventional open TLIF and therefore provides a reduced quantity of local autologous bone, which is usually insufficient to achieve strong intervertebral fusion. However, according to the authors' experience, an adequate amount of bone graft can be obtained during decompression by sequentially removing the IAP, the lower edge of the superior lamina, the upper edge of the inferior lamina, as well as the apical and medial of the SAP. After determining the approximate position of the pedicle with a probe hook during resection of the SAP, an osteotomy can be performed with an oscillating saw or an ultrasonic osteotome. This allows to both reduce cancellous bone bleeding and also obtaining a decent quantity of bone graft, avoiding the loss of small bone fragments caused by continuous flush. Secondly, minimizing the frequency of using burr during the procedure will consent to save a larger amount of bone graft. In addition, a synthetic or allogenic bone graft may be used in case of insufficient autologous bone. When contralateral decompression is performed, we recommend removing first the inferior aspect of the spinous process with an osteotome or high-speed burr using a protective sheath to reduce the risk of dural damage. A curette or Kerrison rongeur may be helpful to remove the contralateral LF. Crossing the midline of the spinous process to reach the contralateral lateral recess, probing the medial wall of the contralateral pedicle, and ensuring that the dural sac and nerve roots are free to move to indicate that the decompression is complete. Preserving the LF is undoubtedly safer; however, in cases where only ipsilateral decompression is required, flavectomy at an early stage provides a wider operative view and helps avoid disorientation during the procedure. However, when performing contralateral decompression, we recommend temporary preservation of ipsilateral LF to reduce the risk of dural and ipsilateral nerve root injury. In particular, in cases with severe LSS, if the ipsilateral LF is removed first, significant expansion of the dural sac can lead to "overtopping" difficulty and increase the risk of injury.

There is a lack of multicenter, large-sample, prospective studies on the efficacy of UBE-TLIF in treating LSS. The concept of the UBE technique was introduced and used for lumbar interbody fusion by Heo (10) in 2017. A total of 69 patients who underwent single-level fusion were reported with an average age was 71.2 years, estimated blood loss was 85.50 ± 19.40 ml, operative time was 165.80 ± 25.50 min, and the follow-up period was 13.5 months. Postoperative MRI showed optimal direct neural decompression, the VAS score and ODI significantly improved, and no case of neurological deterioration was encountered. Kim (11) adopted UBE-TLIF for 14 cases in 2018. The average age of these patients was 68.7 years, postoperative blood loss was 74.0 ± 9.0 ml, operative time was 169.0 ± 10.0 min, and the preoperative VAS score was 7.40, which decreased to 2.70 at 2 months postoperatively. In 2019, Park (25) compared the 1-year follow-up efficacy of UBE-TLIF and conventional PLIF for degenerative lumbar spinal diseases. The mean operative time of the UBE-TLIF group (158.0 min) was longer than that of the PLIF group (137.0 min), and there were significantly more transfusion cases in the PLIF group (20%) than in the UBE-TLIF group (no case). There was a significant improvement in the VAS score of low back pain in the UBE-TLIF group at 1 week, which was significantly better than the PLIF group, but the VAS score of low back pain among patients preoperatively and 1 year postoperatively did not show a statistically significant difference. The VAS scores of leg pain and ODI significantly improved postoperatively in both groups. The clinical results of UBE-TLIF and MI-TLIF in patients with single- or two-segment LSS with or without lumbar spondylolisthesis were compared by Kang (26) in 2021. The VAS score of low back pain and the SF-36 score were more significantly improved in the UBE-TLIF group than the MI-TLIF group at 1 month postoperatively. Nevertheless, the mean VAS scores of low back pain and leg pain, the ODI, and the SF-36 score were not significantly different between groups 1 year after the procedure. Although the total operative time was significantly longer in the UBE-TLIF group, the estimated blood loss and the amount of surgical drainage were significantly more in the MI-TLIF group.

A total of 73 patients completed the procedure in our study. UBE-TLIF is superior to conventional open lumbar fusion reported in an article in terms of estimated blood loss, time to ambulation, and postoperative hospital stay (25). UBE-TLIF operative time is longer than conventional open surgery but shorter than MI-TLIF, as reported by Kim et al. (13), and is probably due to the steep learning curve. Surgeons need to become familiar with the endoscopic anatomy of the spine and carefully stop bleeding to maintain a clear surgical field during the operation. Moreover, discectomy and endplate preparation are often time-consuming surgical steps, especially during early cases (30). A study reported that the technique requires approximately 34 cases to reach an appropriate level of stability (13).

Biportal endoscopic decompression for LSS of 104 and 58 cases was reported by Soliman (21) and Hwa (3) in 2015 and 2016, respectively. UBE has been increasingly used to treat degenerative lumbar spine diseases with wider applications and more satisfactory outcomes. The rate of serious complications associated with the procedure also decreased significantly as the techniques matured. A dural tear is one of the most common complications during endoscopic decompression, with a reported incidence of up to 13.20% (31), while in our study, only two cases (2.74%) of dural tears were encountered. In both cases, the tears were repaired with a gelatin sponge, the skin incision was tightly sutured, and the compressive dressing was applied. In one case, the dural tear occurred during the removal of a central calcified herniated nucleus pulposus and involved the ventral aspect of the dural sac from ipsilateral to contralateral. In the other case, a small dural defect developed during contralateral decompression while removing the LF from the inferior lamina with a Kerrison rongeur. Three patients with a low volume of postoperative drain had a recurrence of leg pain shortly after the drain tube was removed, which occurred because of epidural hematoma formation. However, symptoms completely disappeared after conservative treatment. Two patients who had undergone unilateral laminectomy and bilateral decompression had mild buttock pain the day postoperatively, while this was not reported preoperatively. We hypothesize that symptoms may have been caused by cauda equina stimulation due to the "overtopping" process during contralateral decompression. Nonetheless, symptoms spontaneously resolved after observation. One case presented with temporary dysesthesia in the anterolateral aspect of the left leg and dorsum of the foot with no movement impairment. Also, in this case, symptoms spontaneously resolved after observation. One patient had transient muscle paralysis in both lower limbs as a result of significant intraoperative strain on the dural sac and nerve roots due to the inappropriate retraction at the beginning of the learning curve. Dehydrating drugs, neurotrophic drugs, and functional exercise of lower limbs were used after the operation. Muscle strength was partially improved after 1 week and returned to normal 1 month postoperatively.

A study concluded that the complication rate of UBE decompression of LSS was 6.3% (32). Pranata et al. (33) summarized that the complication rates of UBE and microscopic decompression for LSS were comparable. In another research, Park compared the clinical and radiological outcomes of UBE-TLIF and conventional PLIF for degenerative lumbar spine disease, which summarized that UBE-TLIF was less invasive than PLIF but as effective as conventional PLIF in improving clinical outcomes and obtaining fusion (25). These studies reaffirm the safety and effectiveness of the UBE technique in the treatment of LSS, and it has an extensive surgical view and sufficient operative space to enable traditional open decompression surgery to be performed endoscopically. Combined with the above-mentioned effectiveness, safety, and several advantages, the authors deem that the UBE technique has broad prospects. Nevertheless, the conclusions of this study need to be further validated by the accumulation of more cases and multicenter follow-up results due to this study being a retrospective study with a small sample size and a lack of multicenter studies. The results of this study showed a high complication rate at the beginning of the learning curve and a lack of comparative studies with other fusion procedures to demonstrate the effectiveness and safety of this technique. Furthermore, this study requires further validation of its long-term efficacy and radiological outcomes, including the long-term effects on spinal stability.

Conclusion

UBE-TLIF for LSS has the advantages of less surgical invasiveness and faster postoperative recovery, which is an effective and safe minimally invasive fusion procedure that can provide a reference for treatment options for LSS.

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

The studies involving human participants were reviewed and approved by The Ethics Committee of the First Affiliated Hospital of Xinjiang Medical University. 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

XBW, ZT, and MM: conceptualization and data curation. CW: methodology and formal analysis. ZT: software. AY, LLX, HBX, and LC: validation. MM and HBX: investigation. XBW, MM, and CW: resources. XBW: wrote the manuscript. AY and LC: supervision. CW and LC: project administration. 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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The safe and effective use of supercritical CO_2-processed bone allografts for cervical and lumbar interbody fusion: A retrospective study

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Introduction: The clinical efficacy and safety of supercritical CO_2-processed bone allografts prepared from living donors has yet to be confirmed in spinal surgery. Here we report our clinical and surgical experience of using supercritical CO_2-processed bone allografts for lumbar and cervical fusion.
Methods: Sixteen patients underwent one or two level anterior cervical discectomy and fusion and 37 patients underwent anterior retroperitoneal route lumbar fusion using bone allografts processed using supercritical CO_2 extraction combined with chemical viral inactivation. Fusion success was assessed radiographically in the immediate postoperative period and at one month, six months, one year, and three years postoperatively. Function and pain were assessed using visual analog scales, Odom's criteria, the neck disability index (NDI), and the Oswestry disability index (ODI).
Results: At a mean of 43 and 47 months postoperatively, 95.3% and 90.5% of cervical and lumbar fusion patients had radiographic evidence of bone fusion, respectively. Over 80% of patients reported good to excellent outcomes according to Odom's criteria, the perception of pain significantly decreased, and the mean NDI and ODI scores significantly improved at the last follow-up compared with before the operations. There were no safety concerns. For the cervical group, the mean NDI score improved from 26.3 ± 6.01 preoperatively to 15.00 ± 8.03 and 17.60 ± 13.95 at immediate post-op ($p = 0.02$) and last follow-up visits ($p = 0.037$) respectively. For the lumbar cases, the mean ODI score improved from 28.31 ± 6.48 preoperatively to 14.68 ± 5.49 ($p < 0.0001$) and 12.54 ± 10.21 ($p < 00001$) at immediate post-op and last follow-up visits respectively.
Conclusion: Within the limitations of this study, the use of supercritical CO_2-processed bone allografts resulted in satisfactory clinical outcomes and fusion rates with acceptable safety for both cervical and lumbar surgeries.

KEYWORDS
cervical and lumbar fusion, bone allograft, anterior cervical decompression and fusion, anterior lumbar interbody fusion, supercritical CO_2 treated bone

Introduction

Cervical or lumbar fusion is a good therapeutic option for a range of degenerative disorders that do not respond to conservative therapy, and spinal arthrodesis is an increasingly common orthopedic procedure (1). Autogenous iliac crest bone grafts (ICBGs) have conventionally been used for cervical or lumbar fusion, as this graft is widely accessible and possesses intrinsic osteoconductive, osteoinductive, and osteogenic qualities that promote osteoblastic proliferation and bone tissue development (2).

However, autogenic ICBGs have significant drawbacks including longer operation times and morbidity related to the need for a second donor surgical site (especially infection, hematoma, fracture, and discomfort) (3–6). To enhance fusion, allografts, graft extensions, and osteobiologics have been used as alternatives to ICBG for spinal fusion. All of these procedures achieve their goals by leveraging biological osteoconductivity, osteoinduction, or osteogenesis (7, 8). Fresh frozen or freeze-dried allogenic bone transplants have some advantages over autogenic bone including reduced surgical morbidity, shorter operating times, and higher availability and quantity (9, 10). Histological and histomorphometric data suggest that allogenic bone possesses equivalent osteoconductivity to autogenic bone (11).

Supercritical CO_2-processed bone allografts (Supercrit® BIOBank, Lieusaint, France) are synthesized from human femoral heads obtained from living donors during hip replacement surgery. The femoral heads are cleaned and viruses inactivated using a supercritical CO_2 extraction technique based on delipidation of bone tissue with non-toxic liquid CO_2 in the supercritical state together with chemical oxidation of remnant proteins contained within the pores of the cancellous tissue (12). The procedure does not influence the mineral and collagen content of the bone matrix, retaining the integrity of trabecular bone tissue and mechanical strength equivalent to fresh bone. As a result, supercritical CO_2-treated bone is as osteoconductive as autogenic bone (13, 14). The safety of viral inactivation of Supercrit'® has previously been proven (15, 16). Supercrit® has successfully been used in dental surgery for maxillary sinus elevation (17) for extraction socket grafting (18).

While the efficacy of allogeneic bone grafts has been demonstrated for skeletal defect repair, fracture filling, pseudoarthrosis therapy, and spinal fusion in several systematic reviews (19–22), the clinical efficacy of supercritical CO_2-processed bone allografts has yet to be confirmed in patients undergoing spinal surgery. Here we share our clinical experiences of using Supercrit®-treated bone allografts in patients requiring lumbar or cervical fusion and, in doing so, show that the material is efficacious and safe for this indication.

Methods

Patients

This is a retrospective study with no formal sample size calculation performed. From an initial cohort of 60 cases, we reviewed the data of fifty-three (53) patients treated with the BIOBank supercritical CO_2-processed bone allografts for cervical fusion ($n = 16$ cases representing 21 levels) and lumbar fusion ($n = 37$ cases representing 42 levels) between September 2016 and January 2018, representing approximately 20% of the cases at the institution. Seven patients were lost to follow-up (2 cervical cases and 5 lumbar cases). Enrolment criteria included patients ≥18 years of age with 1or 2-level degenerative disease, with cervicobrachial neuralgia on hernia or disc arthrosis for cervical cases, low back pain or lumbar radicular pain on herniated disc or inflammatory discopathy for lumbar cases. Patients with metastatic tumors or infection were excluded.

Ethical considerations

This study was conducted in accordance with all applicable regulations and with the principles of the Declaration of Helsinki. Due to it retrospective nature, this study came under the French Data Protection Authority Law (the CNIL) Reference Methodology MR004 for approval and thus did not require formal ethical approval. All patients provided consent before any data collection from their files.

Graft material

BIOBank cancellous bone allograft granules processed using Supercrit® technology were used as graft material. Allografts were prepared from living donor femoral heads treated with the supercritical CO_2 process through degreasing steps and gentle chemical oxidation of the residual proteins to preserve the bone architecture. Prior to fusion, bone allograft powder and granules drawn from the cleaned femoral head and packed into a syringe or vial were hydrated with bone marrow blood taken percutaneously with a trocar from the iliac crest.

Surgical technique

All surgical procedures were performed by five senior orthopedic surgeons. All patients were assessed preoperatively to determine their general health status. Cervical arthrodesis was performed *via* the sternocleidomastoid antero-lateral route (ACDF). Fusion was based on complete discectomy followed by abrasion of the vertebral endplates to viable bone before introduction of an interbody cage in PEEK filled with rehydrated allograft powder complemented with an osteosynthesis plate. Lumbar arthrodesis was performed *via* the anterior retroperitoneal route (ALIF). Fusion was based on complete discectomy followed by abrasion of the vertebral endplates to viable bone and then introduction of an interbody cage in PEEK filled with rehydrated allograft powder associated with small fragments of cancellous bone taken minimally from the iliac crest complemented with an osteosynthesis plate.

Outcome measures

Postoperative CT scans were reviewed at the last follow-up. The Bridwell fusion grading system was used to classify fusion on a 4-point scale: grade 1: completely remodeled with trabeculae across disc space; grade 2: graft intact with no lucent lines seen between graft and adjacent endplates; grade 3: graft intact, but a radiolucent line seen between the graft and an adjacent endplate; and grade 4: lucency along an entire border of the graft or lucency around a pedicle screw or subsidence of the graft. Based on this classification system, grade 1–2 was regarded as successful fusion and 3–4 as unsuccessful fusion. All patients were evaluated for graft subsidence and migration on the postoperative CT scan at 12 and 36 months.

Clinical outcomes were measured at baseline, at 12 months, and at the last follow-up using four validated health measurement instruments: the neck disability index (NDI) for cervical patients, the Oswestry disability index (ODI) for lumbar patients, the Odom 4-point rating scale for clinical outcomes after spinal surgery (poor, satisfactory, good, excellent) (23). A 100 mm visual analogue scale (VAS; 0 representing no pain and 100 representing severe pain on activity) for neck and arm pain was used for cervical patients and a VAS for lumbar and radicular pain for lumbar patients. The NDI and ODI score up to 50 points, with higher scores representing greater functional improvement.

Statistical analysis

Statistical analyses were carried out using IBM SPSS Statistics v26 (SPSS Inc. Chicago, IL). Descriptive statistics were analyzed as means (standard deviations, SD) for continuous variables and percentages for categorical variables. Continuous variables were compared using the Wilcoxon-test and categorical variables were analyzed with the chi-squared-test. A p-value < 0.05 was regarded as statistically significant.

Results

Patient characteristics and fusion rates

At the time of this review, follow-up data was available for 53 patients, 15 cervical and 37 lumbar cases. Their mean age was 49 years (range 33–99) and 48 years (range 32–67) for cervical and lumbar groups respectively. There were 8 females and 8 males in the cervical group and 22 females and 15 males in the lumbar group. The mean follow-up was 43 months for the cervical group and 47 months fir the lumbar group. Examples of successful fusion are shown in **Figures 1–3**, and the patient demographics, vertebral locations, and fusion rates are detailed in **Table 1**. The per level fusion rate was 95.3% of cervical cases at 43 months and 90.5% of lumbar cases at 47 months (**Table 1**).

Clinical outcomes

There were significant improvements in all patient-reported outcomes (NDI, ODI, VAS for pain) for function and pain in the immediate postoperative period and at last follow-up compared with baseline (**Table 2**; all $p < 0.05$). For the cervical group, the mean NDI score improved from 26.3 ± 6.01 preoperatively to 15.00 ± 8.03 and 17.60 ± 13.95 at immediate post-op ($p = 0.02$) and last follow-up visits ($p = 0.037$) respectively. The mean VAS neck and arm pain scores also significantly decreased: The mean neck pain decreased from 5.71 ± 2.52 preoperatively to 2.81 ± 2.30 ($p = 0.023$) and 0.53 ± 0.83 ($p = 0.09$) at immediate post-op and last-follow-up visits while the mean arm pain decreased from 5.60 ± 2.43 preoperatively to 1.25 ± 2.37 ($p = 0.018$) and 0.89 ± 2.26 ($p = 0.0013$) at immediate post-op and last follow-up. For the lumbar

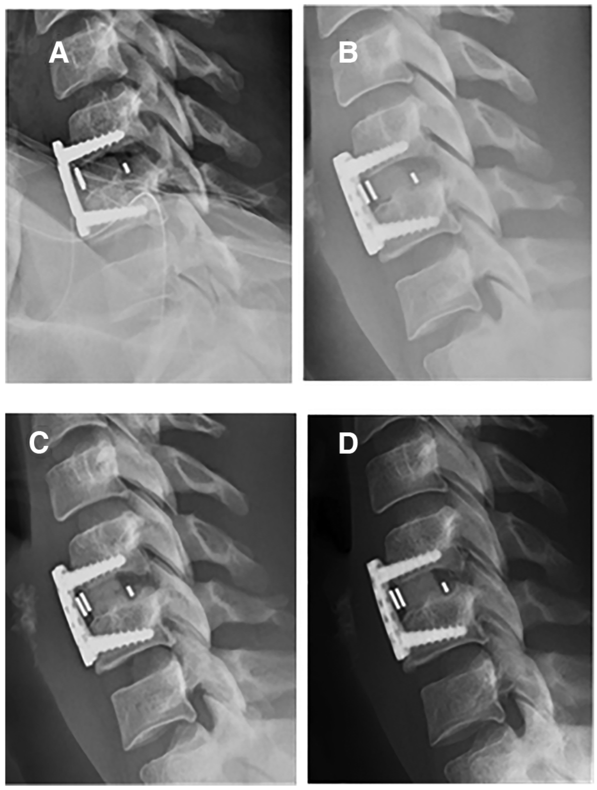

FIGURE 1
One-level ACDF arthrodesis using BIOBank allograft on a 37-year-old female at C5C6. x-Ray lateral view at immediate post-operative (**A**), 1 month postoperative (**B**), 4.5 months postoperative with visible fusion (**C**) and 1 year postoperative (**D**).

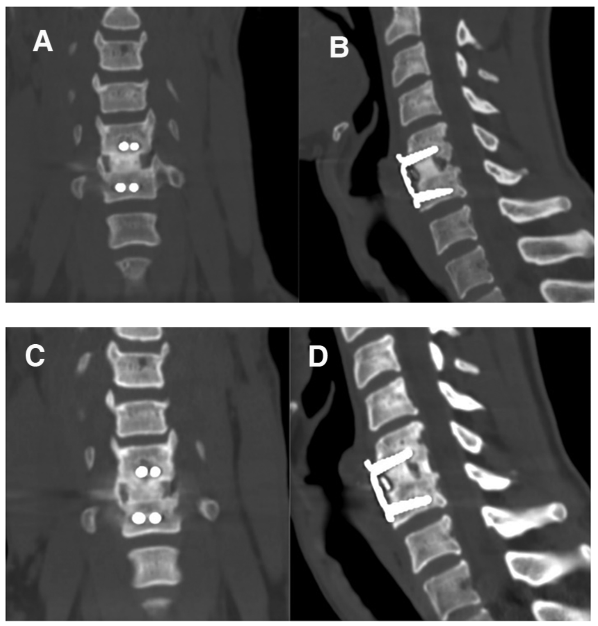

FIGURE 2
Coronal and sagittal computed tomography scans taken 12 months (**A,B**) and 36 months (**C,D**) after surgery showing satisfactory fusions.

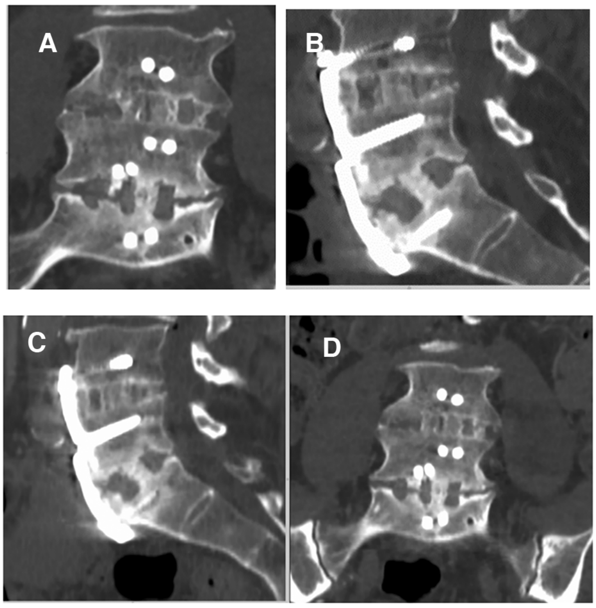

FIGURE 3
Two-level ALIF using BIOBank allograft on a 58-year-old male at L4L5 et L5S1. Coronal and sagittal computed tomography scans taken 14 months (**A,B**) and 36 months (**C,D**) after surgery showing satisfactory fusions.

TABLE 1 Patient characteristics and fusion outcomes.

Variable		Cervical	Lumbar	*P*
Number of patients		16	37	
Gender (%)	Male	8 (50)	15 (40.5)	
	Female	8 (50)	22 (59.5)	0.011
BMI (kg/m²) (mean; range)		24.1 (18.2–29)	24.6 (17.7–36.8)	
Smoking status (%)	Never	12 (75)	24 (65)	
	< 10 packets/year	2 (12.5)	5 (13.5)	
	> 10 packets/year	2 (12.5)	8 (21.5)	
Mean age at surgery (years; range)		49 (33–99)	48 (32–67)	
Operative indications (%)	Foraminal stenosis	15 (71.5)	1 (2.4)	< 0.0001
	Herniated disc	6 (28.5)	2 (4.8)	
	Degenerative disc disease		33 (78.5)	
	Spondylosis		3 (7.1)	
	Pseudoarthrosis		1 (2.4)	
	Revision		1 (2.4)	
	Instability		1 (2.4)	
Number of levels of surgery (%)				
	1-Level	11 (68.7)	29 (78.4)	0.004
	2-Level	5 (31.34)	8 (21.6)	
Fusion location	C3C4	1 (4.8)		
	C4C5	2 (9.5)		
	C5C6	8 (38.1		
	C6C7	7 (33.3)		
	C7T1	3 (14.3)		
	L2L3		1 (2.4)	
	L3L4		3 (7.1)	
	L4L5		14 (33.3)	
	L5S1		24 (57.1)	
Fusion rates (at >42 months)	Successful fusion *n* (%)	20 (95.3)	38 (90.5)	
	Unsuccessful fusion *n* (%)	1(4.7)	4 (9.5)	

cases, the mean ODI score improved from 28.31 ± 6.48 preoperatively to 14.68 ± 5.49 ($p < 0.0001$) and 12.54 ± 10.21 ($p <$ 00001) at immediate post-op and last follow-up visits respectively. The mean VAS lumbar pain significantly decreased 6.62 ± 2.51 to 2.30 ± 2.29 ($p < 0.0001$) and 0.36 ± 0.53 ($p < 0.0001$) and the mean VAS radicular pain from 5.70 ± 2.71 to 1.30 ± 2.41($p < 0.0001$) and 0.19 ± 0.25 ($p < 0.0001$).

Subgroup analysis showed that ODI scores improved from preoperative to last follow-up for both one-level and two-level treated patients. Mean ODI scores changed from 28.5 and 27.7 preoperatively to 12.3 and 13.5 for One-Level ($p < 0.001$) and two-level patients ($p < 0.04$) respectively with no statistically significant difference between groups (**Figure 4**) $p < 0.7$.

VAS lumbar and radicular pain significantly decreased from preoperative to lats follow-up for both one and two-level subgroups (**Figures 5, 6**). Mean VAS lumbar pain decreased from 67.8 preoperatively to 3.6 at last follow-up ($p < 0.0001$) for One-Level and from 60.6 preoperatively to 3.5 at last follow-up ($p < 0.01$) for Two-level groups. Mean VAS radicular pain decreased from 54.1 preoperatively to 1.6 at last follow-up ($p <$ 0.0001) for One-Level and from 67.5 preoperatively to 2.6 at last follow-up ($p < 0.01$) for Two-level groups. Between groups difference was not statistically significant.

Odom's criteria were excellent in 62.5% of cervical patients at the last follow-up, good in 18.7%, and bad in 18.7%, while they were excellent in 43.3% of the lumbar patients at the last follow-up, good in 40.5%, and bad in 16.2% (**Table 2**). Subgroup analysis showed improvement in ODOM criteria from 62% good and excellent at immediate postoperative to 86% good and excellent at last follow-up for One-Level treated patients and from 50% good and excellent at immediate post-operative to 75% at last follow-op for Two-Level treated patients. The improvement was not statistically significant between immediate postoperative and last follow-up visits for both groups. The different was not statistically significant between groups $p < 0.5$.

Safety

No complications were recorded during surgery and at immediate postoperative. There were no adverse events or

TABLE 2 Clinical outcomes from cervical and lumbar fusion.

		Preoperative	Immediate post-operative period	*p*-value (Preop-Immediate post-op)	Last follow-up	*p*-value (Preop – last follow-up)
Cervical						
NDI		26.3 ± 6.01	15.00 ± 8.03	0.020	17.60 ± 13.95	0.037
VAS neck pain		5.71 ± 2.52	2.81 ± 2.30	0,023	0.53 ± 0.83	0.009
VAS arm pain		5.60 ± 2.43	1.25 ± 2.37	0.018	0.89 ± 2.26	0.0013
Odom (% of patients)	Excellent	NA	6.25%		62.5%	<0.06
	Good	NA	87.5%		18.7%	
	Satisfactory	NA	0		0	
	Poor	NA	6.25%		18.7%	
Lumbar						
ODI		28.31 ± 6.48	14.68 ± 5.49	<0.0001	12.54 ± 10.21	<0.0001
VAS lumbar pain		6.62 ± 2.51	2.30 ± 2.29	<0.0001	0.36 ± 0.53	<0.0001
VAS radicular pain		5.70 ± 2.71	1.30 ± 2.41	<0.0001	0.19 ± 0.25	<0.0001
Odom (% of patients)	Excellent	NA	8.1%		43.3%	< 0.08
	Good	NA	83.8%		40.5%	
	Satisfactory	NA	0		0	
	Poor	NA	8.1%		16.2%	

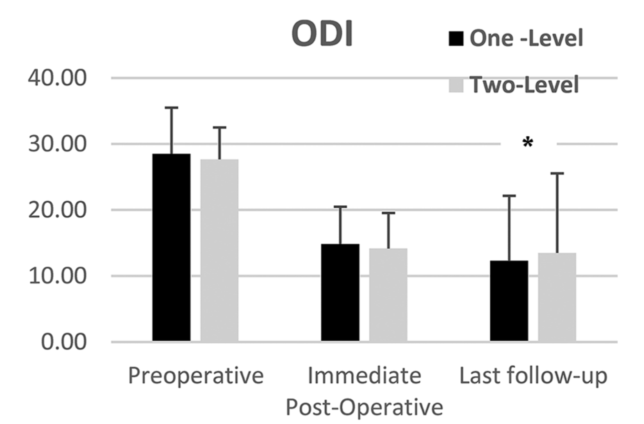

FIGURE 4
Mean ODI scores of one and two-level cohorts at pre-op, immediate post-op, and last follow-up. One-level and Two-Level groups show statistically significant improvement. Error bars represent standard deviation of the means.

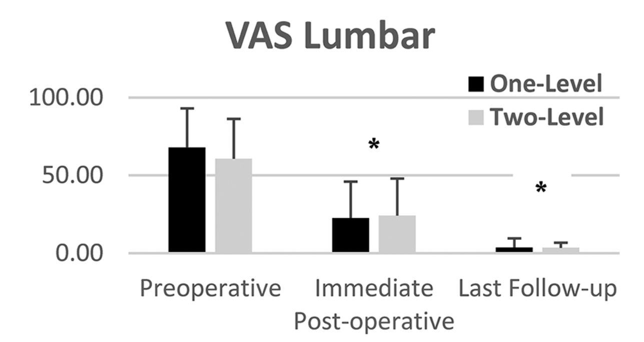

FIGURE 5
Mean VAS lumbar pain of one and two-level cohorts at pre-op, immediate post-op, and last follow-up. One-level and Two-Level groups show statistically significant decrease in pain. Error bars represent standard deviation of the means.

infections related to the allograft that required revisions. There was no neurological deterioration recorded at any time compared with baseline.

After the study completion, one of the four lumbar cases with unsuccessful fusion reported in (**Table 1**) who had anterior approach surgery initially, underwent posterior revision surgery for graft complement and additional screwing for consolidation.

One additional lumbar revision surgery occurred to extend the fusion to the upper level and therefore unrelated to the initial fusion.

Discussion

A variety of biomaterials can be employed for spinal grafting including autografts, allografts, demineralized bone matrix, and/or graft replacements such as ceramic scaffolding devices. To improve fusion rates, a variety of mesenchymal stem cell, growth factor, and synthetic peptide-based approaches have also been tested (24). While ICBG is still the gold standard for cervical and lumbar fusion, it does carry a risk of donor site complications (pain, hematoma, infection) (3–6, 19, 20).

Synthetic bone graft alternatives such as hydroxyapatite (HA) or HA mixed with collagen, tricalcium phosphate, calcium sulfate, or

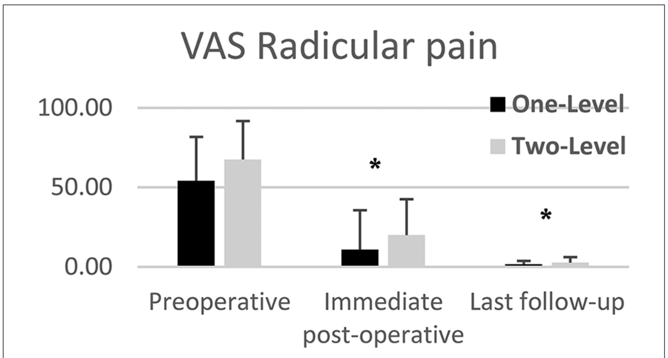

FIGURE 6
Mean VAS radicular pain of one and two-level cohorts at pre-op, immediate post-op, and last follow-up. One-level and Two-Level groups show statistically significant decrease in pain. Error bars represent standard deviation of the means.

polymethylmethacrylate have been reported to increase the risk of graft fragmentation and settling and have more instrumentation issues when compared with ICBGs (25).

Most commercially-available bone allografts (freeze-dried bone allograft, demineralized freeze-dried bone allograft) are made from cadaverous bone processed in a variety of ways including physical debridement to remove soft tissue, ultrasonic washing to remove remnant cells and blood, and delipidation and viral inactivation with strong organic solvents (12). The bone allografts used in this study were manufactured from the femoral heads of living donors harvested during hip replacement surgery and processed using supercritical CO_2 extraction, a technique widely used for organic material splitting, extraction, and disinfection in the pharmaceutical and food sectors. The Supercrit® method includes a degreasing stage with supercritical CO_2 and a moderate chemical oxidation of the remaining proteins in the bone. Preclinical studies have demonstrated that this technique does not influence the composition of bone and retains its architectural and mechanical capabilities, especially its high wettability, thereby preserving performance (13–16).

Allografts have a 93.5% fusion rate when used alone for single- or double-level anterior cervical discectomy and fusion (26) and a 83%–100% fusion rate for lumbar fusion (27). With significant limitations in available literature, systemic reviews conducted in lumbar and cervical spine reported similar effectiveness in terms of fusion rate for allografts compared to ICBG (6, 20). In our study, Supercrit®-processed bone allografts resulted in satisfactory and comparable clinical outcomes, with 95.3% and 90.5% fusion rates for cervical and lumbar surgeries, respectively. Furthermore, for cervical procedures, the allogeneic bone grafts allowed us to avoid autogenic bone graft harvesting altogether, while for the lumbar procedures, use of the allogeneic bone grafts dramatically reduced the volume of iliac crest bone graft required and therefore related morbidity and risks. The use of the material was safe, with reduced surgery time, with no graft site complications nor complications related to the procedure or use of the allograft recorded. Based on this encouraging result, our use of allograft has increased to 50% of our current procedures.

The study has some limitations. It was retrospective with inherent biases. However, we tried to avoid selection bias by doing a wide and careful search and review of patients' records. In addition, the data were recorded prospectively in a standardized manner to reduce any risk of recall bias. The sample size was small due to the single-center nature of the study. The patient population was heterogeneous, some were lost to follow-up, and there was no direct comparative analysis with ICBGs. In addition, the analysis of cervical fusion on CT images was difficult due to the presence of the osteosynthesis material and slices not thin enough.

Conclusions

The use of supercritical CO_2-processed bone allografts appears to be a safe strategy for achieving spinal fusion while limiting the morbidity associated with autograft collection. A larger, randomized controlled study comparing allogeneic and autologous grafts is now warranted.

Data availability statement

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

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

All the authors have contributed equally to this work. 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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Supplementary material

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A novel surgical technique for cervical laminoplasty in patients with multilevel cervical spondylotic myelopathy: A case report and literature review

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Cervical laminoplasty is a posterior-based surgical decompression technique for the treatment of multilevel cervical spondylotic myelopathy (CSM) that may improve the preservation of cervical mobility, spinal canal structure, and natural lordosis. Although this procedure is considered to be comparatively safe, with fewer complications than those seen with laminectomy, several postoperative problems have been noted, including axial neck pain, C5 nerve palsy, and failed resolution of radiculopathy. Hence, various modifications have been made to improve the safety and effectiveness of this technique. Here, we report the case of a 74-year-old man with multilevel CSM who underwent posterior cervical laminoplasty in the C3–C7 segments using a novel surgical technique, termed alternating-side cervical laminoplasty. Preoperative and postoperative assessments, including visual analog scale, modified Japanese Orthopaedic Association, neck disability index scores, and imaging data, were collected and analyzed. The results of a 5-year follow-up indicated that the patient recovered well, with no development of axial neck pain. This is the first report of this modified open-door laminoplasty, which we propose may be a better surgical option for preventing postoperative axial neck pain in patients with multilevel CSM. Additionally, opening the laminae on the alternating sides during laminoplasty could provide a flexible approach to complete decompression on different radiculopathy sides.

KEYWORDS

cervical laminoplasty, multilevel spondylotic myelopathy, alternating side, axial neck pain, novel surgical technique

1. Introduction

Cervical laminoplasty is a posterior technique that can be performed to achieve multilevel posterior decompression of the spinal canal while maintaining alignment and mobility of the spine (1). Initially, this technique was suggested for patients with cervical spondylotic myelopathy (CSM) resulting from multilevel stenosis secondary to ossification of the posterior longitudinal ligament (OPLL). However, it is currently also used for multiple herniated cervical discs accompanying spinal stenosis and multilevel spondylosis-associated spinal cord injury (2, 3). Indeed, cervical laminoplasty was developed as an alternative to laminectomy with the aim of avoiding the original complications of laminectomy alone (4), such as postoperative segmental instability, recurrence of spinal cord compression, kyphosis, perinerve adhesion, late neurological deterioration, and so on (5).

Based on laminectomy, the first laminoplasty technique termed Z-plasty was introduced by (6, 8). This technique involved removal of the spinous process, thinning of the laminae in which the z-shaped cuts were made next, followed by elevation and fixation with sutures to reconstruct the expanded spinal canal. Unfortunately, owing to its complicated procedure, Z-plasty was not widely available. After the 1970s, Hirabayashi et al. reported the open-door laminoplasty, while Kurokawa et al. developed the double-door laminoplasty technique (also called French-door laminoplasty or spinous process-splitting laminoplasty) (9, 10). The former involved excision of the lamina border on one side and drilling of the bony gutter on the other side so that the lamina would be pushed laterally as if to open a door, while the latter involved opening the spinal canal in the midline bilaterally (like a French-door) by splitting the spinous process. Since these two prototype techniques were original published, various modifications of cervical laminoplasty have been developed with the aim of improving the safety and effectiveness of the procedure (**Table 1**). For example, Hirabayashi et al. secured the laminae to the facet by using sutures, while O'Brien et al. used titanium miniplates for security (11). In addition, in the Tomita and Morimoto modifications (12, 13), bone graft was used as a spacer in the final step of the French-door laminoplasty, including later ceramic laminas and hydroxyapatite spacers (14–16). More recently, several clinical studies have focused on preserving muscle attachment to enable dynamic stabilization of the cervical spine by the neck extensor muscles (17–20).

Although considerable progress has been made in the last few decades, some challenges induced by laminoplasty—such as kyphosis, axial neck pain, and C5 nerve palsy, which can have a significant impact on patients' quality of life—are yet to be solved (21). In order to optimize these postoperative residual problems, instrumented techniques are constantly being innovated with the invention of new internal fixation devices (22, 23). Nevertheless, few reports have focused on modifications of the original technique. In the present study, we review the case of one patient who underwent a novel surgical cervical laminoplasty to evaluate whether this modification resulted in any beneficial effects, and further provide a review of literature to discuss modifications to the technique.

2. Case presentation

2.1. Patient characteristics

We present the case of a patient who underwent cervical laminoplasty in the C3–C7 segments, performed in 2017. The 74-year-old man was admitted to our center with complaints of loss of strength and persistent numbness in his upper limbs for 2 years. Additionally, he experienced progressive walking disturbance in both legs for 1 year.

Upon admission, the patient's general condition was normal, except for a visual analog scale (VAS) of neck pain score of 3, modified Japanese Orthopaedic Association (mJOA) score of 8, and neck disability index (NDI) score of 26, indicating severe dysfunction. Neurological examination revealed right-side dominant weakness (i.e., power as evaluated by manual muscle testing: 4/5 for the deltoid muscles, biceps, and triceps of the right upper limb, and the same for the wrist flexors and wrist extensor, except for the finger flexor, the finger extensor, and the intrinsic muscles of the hand, which were normal), hypesthesia of the radial side of the right forearm and right thumb, and a right positive Hoffmann's sign. Bilateral hyperreflexia of the patellar reflex, right hyperreflexia of the ankle reflex, and a positive Babinski test result were also observed. Radiographic

TABLE 1 Development of the surgical technique of cervical laminoplasty.

Type	Representative	Technical feature	Advantages of modification
Lamina-Z-plasty	Oyama et al. (1973) (8)	Z-shaped cuts made in each lamina and fixed with sutures	Retains support; prevents "laminectomy membrane" formation
Open-door laminoplasty	Hirabayashi et al. (1978) (9)	Elevates the laminae on the hinge, secured to the facet using sutures	Operative technique is relatively easy and safe
Double-door laminoplasty	Kurokawa et al. (1982) (8)	Spinous processes are split in the midline and are maintained open	Achieves symmetrical expansion of the spinal canal
Hardware-augmented	Hase et al. (1991) (15)	Uses ceramic laminas	Provides a simpler, safer, and more effective method of fixation
	Nakano et al. (1992) (16)	Uses a hydroxyapatite spinous process spacer	
	O'Brien et al. (1996) (11)	Uses titanium miniplates to secure the elevated laminae	
Muscle-sparing	Shiraishi (2002) (34)	Preserves the attachments of the semispinalis and multifidus muscles to the spinous processes	Reduces postoperative axial pain
	Takeuchi et al. (2005) (20)	Preserves the semispinalis cervicis insertion into C2	
	Hosono et al. (2006) (19)	Preserves the C7 spinous process and the origin of the trapezius and rhomboideus minor muscles	
Instrumented	Lee et al. (2016) (23)	Insertion of translaminar screws, fixed in the contralateral lateral mass	Maintains spinal stability and prevents postoperative axial pain and deformity
	Nasto et al. (2017) (22)	Uses trapezoidal maxillofacial titanium miniplates with bone graft for fixation	Safe, reproducible, and alternative technique

examination, including anteroposterior, lateral, hyperextension, and flexion radiographs of the cervical spine, showed that the height of intervertebral spaces was decreased in the C3–C7 segments, notably at the C4–C5 and C6–C7 levels. In addition, with degenerative changes at the edges of the vertebrae and straightening of the physiological curvature, the cervical spine range of motion was diminished, but remained relatively stable (**Figures 1A–D**). Sagittal computed tomography (CT) of the cervical spine further showed osteophytes formation at the anterior edges of the vertebrae of C4–C7 and multilevel spinal canal stenosis (**Figure 2A**). Furthermore, magnetic resonance imaging (MRI) demonstrated cervical stenosis at the C3–C7 levels with varying degrees of disc herniation and compression of corresponding dural sacs and spinal cord, particularly severe at the C3–C4 and C4–C5 levels (**Figure 2B**). CSM was diagnosed based on the patient's clinical presentation and imaging findings. Posterior cervical laminoplasty (PCL) at the C3–C7 levels was deemed necessary to decompress the spinal canal.

Considering the safety and stability of the present surgical techniques, open-door laminoplasty and fixation with plates is generally preferred in our hospital. During the preoperative conversation, the patient highlighted the need to minimize postoperative neck pain as much as possible, as this had already considerably reduced his quality of life. However, in this unilateral open-door laminoplasty, an asymmetric expansion of the canal is created, resulting in skeletal and muscular asymmetry, which may further lead to postoperative axial pain (24, 25). In light of this problem, our team has designed a novel surgical technique in which the laminar door is opened alternatively to conserve the posterior structure of cervical spine symmetry in an attempt to reduce axial pain. A finite element (FE) analysis has been performed in advance, confirming that this technique preserves the symmetry of the cervical structure, thereby promoting improved balance during right and left lateral flexion and rotation.

Given the patient's needs, we believed that this surgery was suitable and that it may be able to achieve satisfactory results. As such, the patient and his family were fully informed of the risks and benefits of the procedure, and informed consent was obtained. The patient underwent surgery in March 2017.

2.2. Surgical procedure

The patient was placed in a prone and reverse Trendelenburg position. His head and neck were kept in slight flexion using a Mayfield head holder, with the sagittal line of the neck parallel to the floor. The bony landmarks were palpated to determine the level of the C7 spinous processes. First, a midline posterior approach focusing on C2–C7 was performed, and the laminae were exposed to the midportion of the lateral masses so that the muscle origins over the lateral half could be preserved. The

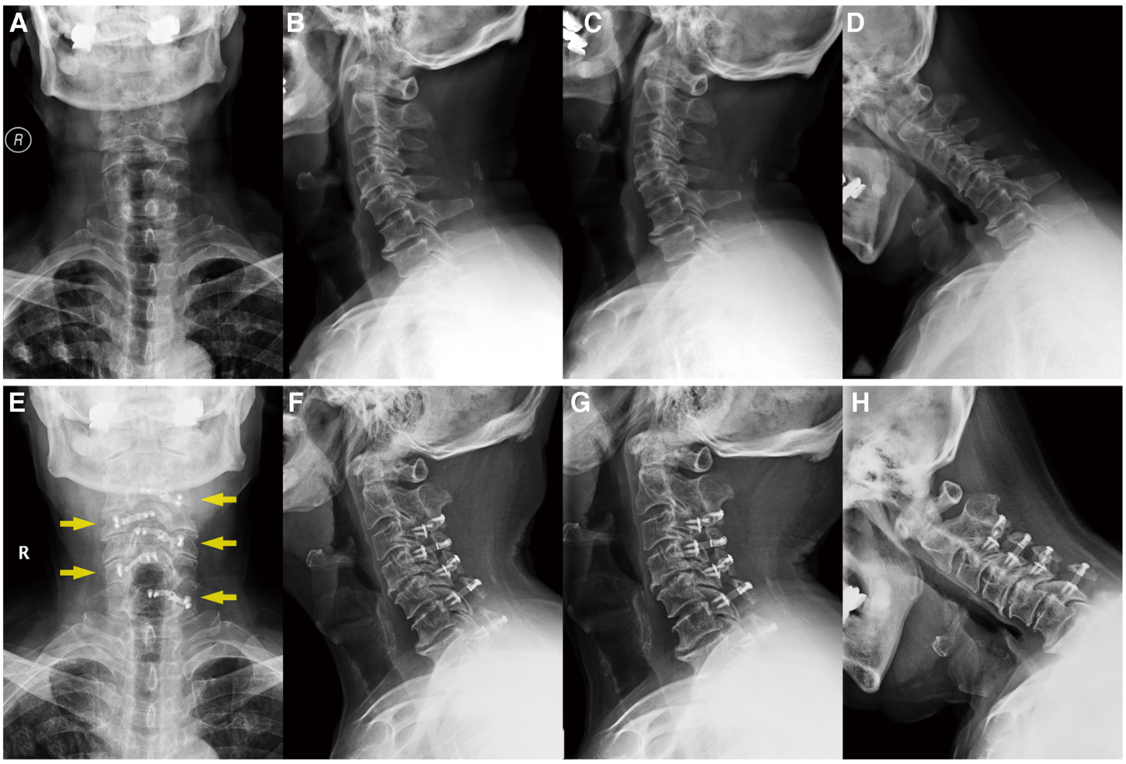

FIGURE 1
(A–D) Preoperative x-rays of the cervical spine (anteroposterior, lateral, hyperextension, and flexion radiographs, respectively), showing that the vertebral physiological curvature straightened with a certain degree of degenerative change. (E–H) Postoperative x-ray after 5 years, demonstrating the position of the internal fixation plates (yellow arrows) and that the cervical curvature and the range of motion have remained the same.

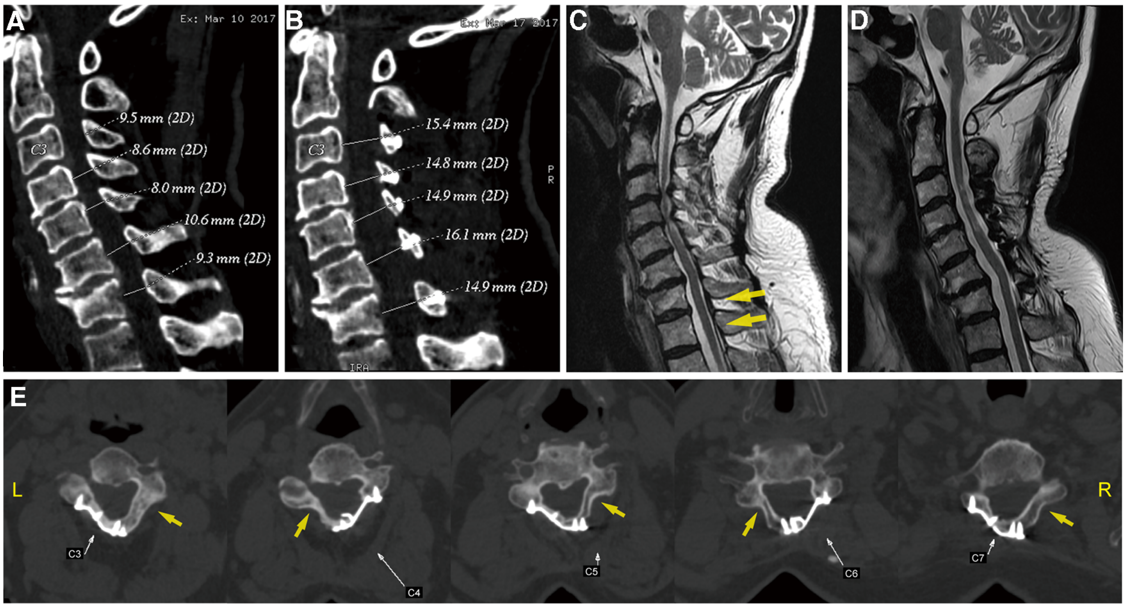

FIGURE 2
(**A,B**) Preoperative and postoperative sagittal CT scans, illustrating the changes in the cervical spinal canal diameter. Sagittal T2-weighted MR images: (**C**) preoperative scan, showing a cervical stenosis and varying degrees of disc herniation at the C3–C7 levels, with particular severeness at C3–C4 and C4–C5 (yellow arrows); (**D**) 5-year postoperative scan, showing adequate spinal cord decompression. (**E**) Axial CT scan of the operated segments 5 years after the operation, suggesting a large fusion on the laminar hinge position (yellow arrows) and that the laminar doors have been kept open by the plates. CT, computed tomography; MR, magnetic resonance.

extensor muscles were subsequently detached from the lower laminar margin of C2 to allow access to the C2–C3 interlaminar space. Second, the spinous processes of C3–C7 as well as part of the lower laminar margin of C2 and the upper laminar margin of C7 were removed using a Kerrison rongeur. Bone wax was used to achieve hemostasis on the bone surfaces. Third, the junctions between the lateral parts of the lamina and the lateral mass were identified at each level where the side troughs were prepared. The junctions were thinned using a high-speed drill until the dorsal cortex was removed, forming hinge side troughs, which yielded slightly with a moderate bending force. On the contralateral side, the junctions were excised to construct the open side troughs, and the ligamentum flavum, facet capsules, and veins were carefully divided, as required. It is worth noting that this procedure requires transverse excisions of the ligamentum flavum in each laminar space from C2 to T1 to allow the adjacent laminae to be independent. After the adhesions have been separated from the dura by the use of a nerve hook, the laminae are gradually opened by applying a slight opening force.

In contrast to the traditional open-door laminoplasty, which involves opening of the unilateral side of the spinal canal, we designed this technique to open the laminae on the alternating side. Thus, the hinge side trough was made on the right and the open side trough on the left at the C3, C5, and C7 segments, while the hinge side trough was made on the left and the open side trough on the right at the C4 and C6 segments, so that the laminar doors opened alternatively from C3 to C7. Subsequently, all the laminae were lifted, and an appropriately sized laminoplasty plate was selected for each level using a bone trial. Then, self-tapping screws were inserted using a self-holding screwdriver to anchor the centerpiece plates (SOFAMOR DANEK, Medtronic, Memphis, TN, United States) to the lateral mass and lamina at each segment for stabilization and support. Finally, we checked whether the decompression was sufficient and observed the placement of the plate *via* bedside radiography, and adjustments were made until a satisfactory result was obtained. A deep drain was placed and the wound was closed.

2.3. Postoperative information

After the surgery, the patient wore a Philadelphia collar for a month. X-ray and CT imaging of the cervical spine were performed again on the third day after removal of the drain. Anteroposterior and lateral radiographs suggested that the posterior cervical plates were well positioned and firmly fixed. CT scans of the sagittal spinal canal showed that the diameter was increased compared to before surgery (Figure 2C). Meanwhile, a three-dimensional reconstruction was performed to clearly visualize the posterior structure of the postoperative cervical spine, from which it was observed that the laminae from C3 to C7 were open and evenly fixed on both sides, rather than only on one side, as is traditionally seen (Figures 3A,B).

A week later, the patient's neck pain had markedly diminished, the symptoms of weakness in both lower limbs were relieved, and the patient was able to walk with the help of walking aid. Although the patient retained some residual muscle strength in his right hand, physical examination revealed weakness in the right upper limb (power as evaluated by manual muscle testing:

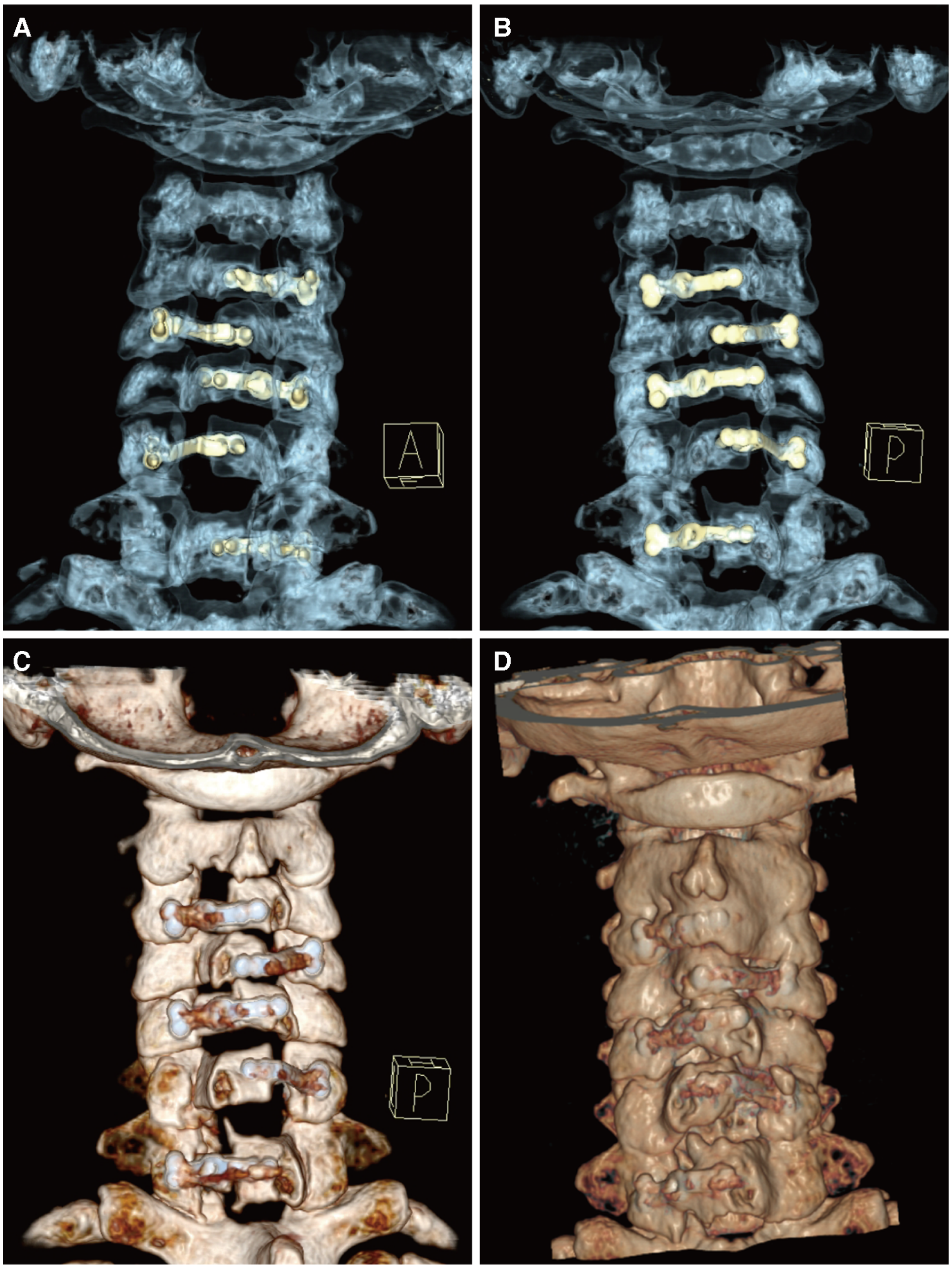

FIGURE 3
(A,B) Three-dimensional reconstructions of CT images (A: anterior view, B: posterior view), to allow clear visualization of the operating feature of the internal fixation plates during this novel technique. (C,D) Posterior views of the reconstructed cervical spine structure (C: 1 week postoperatively, D: 5 years postoperatively), showing the fixation and integration of the implanted plate with the posterior lamina. CT, computed tomography.

4/5 for the deltoid muscles, biceps, and triceps), which was almost the same as before surgery. The total hospital stay in the conventional spine surgery department was 2 weeks, and the patient had virtually no neck pain, corresponding to a VAS score of 1, an mJOA score of 12, and an NDI score of 18, indicating moderate dysfunction.

Five years later, the patient returned to our hospital to undergo follow-up and complete tests. The patient was able to walk slowly on his own without the help of crutches, although handrails were needed to climb up and down the stairs. The weakness in his right upper limb had improved slightly, allowing him to use a spoon. Overall, the symptoms of spinal cord compression were relieved. The patient's neck pain was completely absent, as expected. In addition, a series of x-rays showed that the position of internal fixation was well maintained, without significant loosening or displacement, and the cervical curvature and range of motion were the same as before (Figures 1E–H). Furthermore, axial CT scans of the operated cervical segments suggested a good fusion at the laminar hinge position, while the laminar doors were firmly kept open (Figure 2E), and the implanted plates were well fused with the posterior lamina, supported by the three-dimensional CT (**Figures 3C,D**). Finally, the MRI results revealed that the operated spinal canal had expanded sufficiently for the spinal cord to decompress adequately and that the operation had little effect on the symmetry of the posterior cervical muscles after 5 years (**Figure 2D**). According to a questionnaire administered to the patient, it was noted that the VAS score was 0, the mJOA score increased to 14, and the NDI score decreased to 12 already, indicating mild dysfunction. In summary, the patient experienced moderate improvement following surgery.

3. Discussion

Cervical laminoplasty, which ensures indirect posterior decompression by expanding the spinal canal to allow the spinal cord to migrate dorsally, is an effective method for patients with multiple disk herniations or OPLL (1). Although associated techniques have been continuously refined since its introduction, laminoplasty can be broadly categorized as unilateral open-door laminoplasty or double-door laminoplasty. Compared with the latter technique, which requires more surgical manipulations and one of which is performed directly on the midline of the compressed spinal cord, the former technique tends to be selected.

The original open-door laminoplasty expands the spinal canal by hinging the posterior arch on one side at the junction between the lamina and the lateral mass, while complete osteotomy is performed on the other side with greater compression and symptoms. The laminar door is kept open with the use of stay sutures that are placed through the spinous process and the facet capsule or the paravertebral muscle on the hinge side (9, 26). Later studies have described the use of suture anchors in the lateral mass for suture fixation and the use of translaminar screws to prevent door reclosure (23, 27). Although modified suture fixation techniques have substantially improved, surgeons began using more rigid fixation in the form of bone blocks and plates (**Table 1**) (11, 13, 28). Currently, plates are generally preferred because of their ease of application and the provision of immediate, stable fixation (29).

However, one of the criticisms of traditional open-door laminoplasty is the potential for increased axial neck pain (30). Ohnari et al. previously showed that the incidence of axial neck pain after laminectomy is 82.3%, which was significantly increased from the incidence of 59.1% before surgery (31). Furthermore, studies have suggested that axial symptoms may be caused by several problems, such as posterior extensor musculature intraoperative injury, destruction of the facet joints, and intraoperative nerve root damage (30, 32). Notably, during unilateral open-door laminoplasty, the canal is opened on one side and hinged on the other, which essentially creates an asymmetric expansion of the canal, further resulting in skeletal and muscular asymmetry that may result in postoperative axial pain and may further produce forces on the opened side, which can result in restenosis. Another issue with open-door laminoplasty is the lack of affordability for foraminal decompression at different sides due to its unilateral design. When radiculopathy exists simultaneously with different-sided foraminal stenosis, open-door laminoplasty may not be able sufficient to adequately relieve the patient's radicular symptoms well because of inadequate foraminal decompression or asymmetrical decompression.

Taking these challenges into consideration, our novel technique proposed the maintenance of spinal alignment, muscular symmetry, and motion force balance to reduce the associated pain. Distinct from the traditional procedure, construction of the hinges on the opposite sides of adjacent cervical segments meant that the laminar door could be opened alternatively from one end to the other in the cervical spine; thus, we termed this technique the alternating-side cervical laminoplasty. In the present study, we reported our experience with the case of a patient with cervical spondylotic myelopathy who agreed to undergo this novel procedure in 2017. Finite element (FE) analysis was performed before clinical surgery; it had validated that the postoperative structure after the novel technique employed would be beneficial in ensuring a balancing motion of the cervical spine. Furthermore, to ensure the stenosis of the neural foramen on different sides, this technique offered a flexible approach to choose an open side to decompress the neural foramen expediently as well as the canal. It could be expected that this technique would allow the intraoperative operation of multisite decompression to be simplified and the axial neck pain to be reduced. Optimistically, the strong postoperative recovery of the patient in our case also supports the use of this modification. Additionally, another alternative technique for reducing axial neck pain has been described, which involves the preservation of muscle attachment (33, 34). Riew et al. previously showed that surgeons should make every effort to preserve soft tissue on the C2 and C7 whenever possible as there appears to be a little downside to doing so, while reducing the incidence of postoperative neck pain (35). Therefore, we propose that the two modification techniques mentioned above can be applied simultaneously to minimize the occurrence of axial neck pain in the future.

4. Conclusion

Cervical laminoplasty represents a safe and effective posterior technique to achieve adequate exposure and decompression of the spinal canal required for the treatment of multilevel cervical spondylotic myelopathy. Here, we reported a case treated with a novel surgical technique for cervical laminoplasty, called the alternating-side cervical laminoplasty. This technique was proposed to maintain spinal alignment and muscular symmetry as much as possible by opening the laminar door alternatively, while simultaneously facilitating decompression of the neural foramen. Postoperative results after 5 years of follow-up showed that the patient experienced significant relief from his preoperative symptoms, with complete resolution of neck pain. Thus, besides preserving muscle attachment, the modified procedure mentioned above may be used to prevent postoperative axial pain. Certainly, a large number of clinical applications and postoperative results should be obtained to further evaluate its effectiveness before advocating it for popular implementation.

Data availability statement

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

Ethics statement

Written informed consent was obtained from the individual for the publication of any potentially identifiable images or data included in this article.

Author contributions

XH was responsible for interpreting the study, drafting the article, and creating figures. DL was responsible for interpreting the study, following up with the patient, and collecting data. YY and HQ were responsible for assisting in the collection of data and revising the work. ZM was responsible for revising the work. WL and YZ were responsible for designing, supervising, and interpreting the study. All authors agreed to be accountable for all aspects of the work. 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.

Publisher's note

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Comparisons of oblique lumbar interbody fusion and transforaminal lumbar interbody fusion for degenerative spondylolisthesis: a prospective cohort study with a 2-year follow-up

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Objective: This study aimed to compare the clinical outcomes between oblique (OLIF) and transforaminal lumbar interbody fusion (TLIF) for patients with degenerative spondylolisthesis during a 2-year follow-up.

Methods: Patients with symptomatic degenerative spondylolisthesis who underwent OLIF (OLIF group) or TLIF (TLIF group) were prospectively enrolled in the authors' hospital and followed up for 2 years. The primary outcomes were treatment effects [changes in visual analog score (VAS) and Oswestry disability index (ODI) from baseline] at 2 years after surgery; these were compared between two groups. Patient characteristics, radiographic parameters, fusion status, and complication rates were also compared.

Results: In total, 45 patients were eligible for the OLIF group and 47 patients for the TLIF group. The rates of follow-up were 89% and 87% at 2 years, respectively. The comparisons of primary outcomes demonstrated no different changes in VAS-leg (OLIF, 3.4 vs. TLIF, 2.7), VAS-back (OLIF, 2.5 vs. TLIF, 2.1), and ODI (OLIF, 26.8 vs. TLIF, 30). The fusion rates were 86.1% in the TLIF group and 92.5% in the OLIF group at 2 years ($P = 0.365$). The OLIF group had less estimated blood loss (median, 200 ml) than the TLIF group (median, 300 ml) ($P < 0.001$). Greater restoration of disc height was obtained by OLIF (mean, 4.6 mm) than the TLIF group (mean, 1.3 mm) in the early postoperative period ($P < 0.001$). The subsidence rate was lower in the OLIF group than that in the TLIF group (17.5% vs. 38.9%, $P = 0.037$). The rates of total problematic complications were not different between the two groups (OLIF, 14.6% vs. TLIF, 26.2%, $P = 0.192$).

Conclusion: OLIF did not show better clinical outcomes than TLIF for degenerative spondylolisthesis, except for lesser blood loss, greater disc height restoration, and lower subsidence rate.

KEYWORDS

interbody fusion, comparative study, OLIF, spondylolisthesis, cohort study

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Introduction

As a minimally invasive approach, oblique lumbar interbody fusion (OLIF) was first introduced by Silvestre et al. in 2012 (1). For patients with lumbar spinal deformity requiring corrective surgery and multiple-level fusion, OLIF is superior to the conventional posterior lumbar fusion techniques, as better angular correction, less blood loss, and less severe surgical trauma were achieved by OLIF (2).

For degenerative spondylolisthesis, lumbar interbody fusion is one of the most common procedures, and different surgical approaches have been reported, including anterior, posterior, transforaminal (TLIF), and lateral (3). Through a muscle-splitting approach, OLIF allows for large-size cage insertion, producing indirect decompression by enlargement of the spinal canal and intervertebral foramen (4). The clinical outcomes in previous studies are effective for degenerative spondylolisthesis by OLIF with indirect decompression and short-level fusion (5, 6). However, whether OLIF is superior to the conventional TLIF for degenerative spondylolisthesis concerns many surgeons. Few comparative studies were retrospective and showed inconsistent results with short-term follow-ups (7–9).

This prospective study aimed to compare the clinical outcomes between OLIF and TLIF for patients with degenerative spondylolisthesis during a 2-year follow-up.

Materials and methods

Study design

This is a prospective cohort study comparing the treatment effect between two groups: patients who underwent OLIF or TLIF. The protocol of this study was approved by the ethical committee of the authors' hospital, and informed content was obtained for all eligible patients.

The sample size was estimated to be 45 patients for each group, with 80% power to detect the between-group difference of 10 on the magnitude of Oswestry disability index (ODI) improvement at a two-sided significance level of 0.05. A difference of 16 ODI improvement between OLIF and TLIF groups, which was derived from previous studies (6, 10), an SD of 10 for the ODI improvement, and a rate of loss to 2-year follow-up of 20% were assumed.

Patient population

Eligible patients who underwent OLIF were prospectively and consecutively enrolled from July 2017, and those who underwent TLIF were enrolled from January 2018 in the authors' hospital. The inclusion criteria were symptomatic radiculopathy or claudication, which was disabling and intolerable for more than 3 months with failed conservative management, degenerative spondylolisthesis, Meyerding grade I or II slip, unstable slip evidenced by mechanical low back pain with excessive motion on flexion–extension lumbar radiographs, and planned single-level or two-level fusion. The fusion extending to the adjacent level with symptomatic spinal stenosis was also eligible. The exclusion criteria were lumbar scoliosis greater than 30°, concomitant infection, tumor or fresh fracture at the lumbar spine, previous lumbar surgery, coexistent pathology at hip or knee joint causing unremitting leg pain or severe disability, previous knee or hip joint replacement, and rheumatoid arthritis.

The choice of OLIF or TLIF depends on the surgeon's preference and the patient's consent. All surgeons were experienced with at least 50 surgical cases for OLIF or TLIF they performed in this study.

Procedures

OLIF was performed according to the Medtronic OLIF25 surgical technique. An appropriate size of 6° lordotic cage (18 mm in width, CLYDESDALE Spinal System, Medtronic) was inserted into proper position, which was confirmed by fluoroscopy. The bone grafts in the cage were allografts mixed with demineralized bone matrix (AlloMatrix, Wright Medical). Posterior fixation at the prone position was performed. Percutaneous pedicle screw fixation was performed if indirect neural decompression was appropriate for selected patients.

Patients with one of the following conditions underwent direct neural decompression and open fixation: preoperative radiating pain at bed rest, migrating disc or ossification at the spinal canal, and ankylosed facet joint. For these patients, partial laminectomy or laminotomy and pedicle screw placements were performed.

TLIF was performed in an open fashion at the prone position. Through the posterior midline approach, pedicle screws were inserted. Afterward, unilateral facetectomy, neural decompression, endplate preparation, and insertion of the PEEK cage with morselized autograft were performed. Patients with bilateral neurological symptoms underwent bilateral decompressions; otherwise, unilateral decompression was performed during TLIF procedures.

Outcome measures

The pain intensity and severity of disability were measured using the self-reported visual analog score (VAS) and ODI. The primary outcomes are treatment effect (changes of VAS and ODI from baseline) at 2 years after surgery.

The enrolled patients were followed up at 3, 6, 12, and 24 months by two coordinators (TG and GL). VAS and ODI were collected through an online survey tool at each timepoint of follow-up. Patients returned to the authors' hospital for radiographic assessment at 3, 12, and 24 months. Standing anteroposterior, lateral, and flexion–extension radiographs were obtained. CT scans were obtained at the last follow-up (2 years or more).

Radiographic parameters include disc height (DH), anterior DH (DHA), posterior DH (DHP), and segmental lordosis (SL) at the slip level (see **Figure 1**). These parameters were measured on the lateral standing radiographs before the operation, during the early postoperative period (within 3 days), and at the last follow-up.

The fusion status was assessed on flexion–extension radiographs and CT scans at the last follow-up. Less than 5° rotation and 3 mm displacement (indicating excessive motion) on flexion–extension radiographs and grade I or II bone bridging on CT scans were regarded as fusion; otherwise, failure of fusion was considered. The grading method of bone bridging was described by Isaacs et al. (11). Endplate injury was confirmed if endplate encroachment was greater than 2 mm on the early postoperative radiograph. Cage subsidence was measured on CT scans at the last follow-up using the grading method described by Marchi et al. (grade I–III, higher grade indicating severe subsidence) (12).

Two orthopedic surgeons (JA and ZX) were trained and measured radiographic parameters independently on Carestream PACS (version 11.0). Fusion status, endplate injury, and cage subsidence were also assessed by these surgeons. The agreement of the measurement was evaluated by an interclass correlation coefficient (>0.75 is acceptable). The mean value of the two observers' results was used for statistical analysis. If grading inconsistency existed between two observers, a third observer (J.W) would ultimately confirm the grade.

The surgical complications for each group were evaluated. The complications comprised mechanical complications (fusion status, endplate injury, cage subsidence, or failure of fusion), neurological injury, visceral injury, surgical site infection, excessive bleeding, and death.

Statistical analysis

Comparisons of continuous variables between two groups were performed by using an independent sample *t*-test if normal distributions were confirmed by the Shapiro–Wilk test.

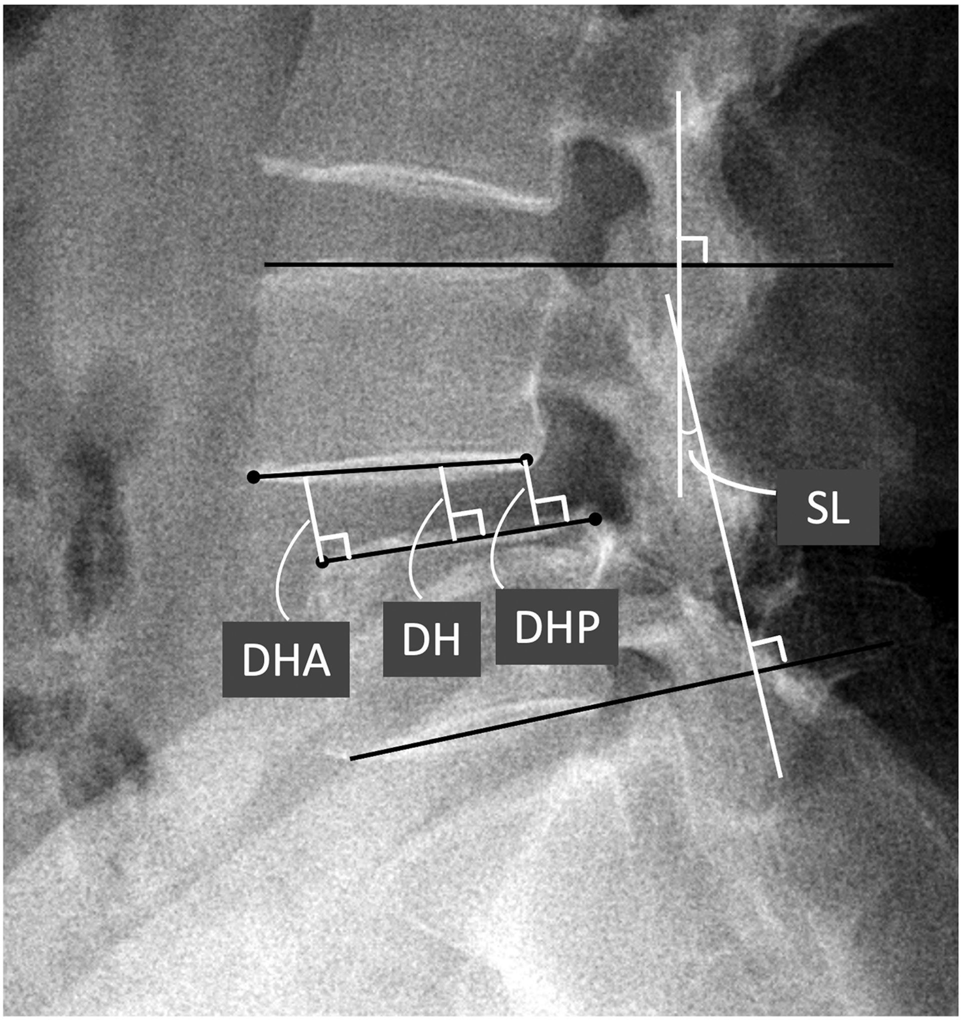

FIGURE 1
Definitions of radiographic parameters. SL, DH, DHA, and DHP on the standing lateral view of lumbar spine. SL, segmental lordosis; DH. disc height; DHA, anterior DH; DHP, posterior DH.

Otherwise, nonparametric analysis was performed by using the Mann–Whitney *U* test. For categorical variables, the differences between two groups were analyzed by a χ^2 test.

The statistical analyses were performed using SPSS software, IBM SPSS Statistics, version 23.0. The statistically significant level of difference was assumed at $P < 0.05$ based on a two-sided hypothesis test.

Results

A total of 45 patients were eligible for the OLIF group and 47 patients for the TLIF group. Forty patients finished the 2-year follow-up in the OLIF group and 41 patients in the TLIF group (the workflow of the follow-up is shown in **Figure 2**). The rates of follow-up were both greater than 80%. Case examples of OLIF and TLIF were shown on **Figures 3**, **4**.

Patient characteristics

Patient characteristics were shown in **Table 1**. Higher proportion of two-level fusion (51.2%) was found in TLIF group than did the OLIF group (27.5%). The duration of operation in OLIF group (mean, 190.3 min) was longer than those in TLIF group (mean, 157 min) ($P = 0.001$). OLIF group had less estimated blood loss (median, 200 ml) than did TLIF group (median, 300 ml) ($P < 0.001$). Thirteen cases had greater than 500 ml blood loss and two cases greater than 1,000 ml blood loss in TLIF group, whereas no OLIF cases producing greater than 500 ml blood loss. Patients in OLIF group stayed slightly shorter period in hospital postoperatively than those in TLIF group ($P = 0.035$).

Primary outcomes

The comparisons of treatment effects at 2 years between the two groups demonstrated no difference for changes of VAS-leg (OLIF, 3.4 vs. TLIF, 2.7), VAS-back (OLIF, 2.5 vs. TLIF, 2.1), and ODI (OLIF, 26.8 vs. TLIF, 30). The results of comparisons during follow-up are shown in **Table 2**.

The comparisons of preoperative scores showed no significant difference, except the mean VAS-leg (OLIF, 5.7 ± 1.9 vs. TLIF, 4.9 ± 1.5, $P = 0.041$). During follow-up, TLIF group had slightly less back pain than did the OLIF group at 3 months, 6 months, and 1 year; however, the difference between groups became nonsignificant at 2 years ($P = 0.411$). The VAS-leg and ODI were similar between two groups during each follow-up, except ODI at 6 months (OLIF, median: 22 vs. TLIF, median: 18, $P = 0.041$).

Due to the heterogeneity in proportions of two-level fusion between groups, subgroup analysis was performed (**Table 3**). For one-level fusion, the OLIF group (mean, 3.6) had a greater reduction of leg pain at 2 years than did TLIF group (mean, 2.5) ($P = 0.049$), which was also clinically meaningful difference. For two-level fusion, however, no difference was found.

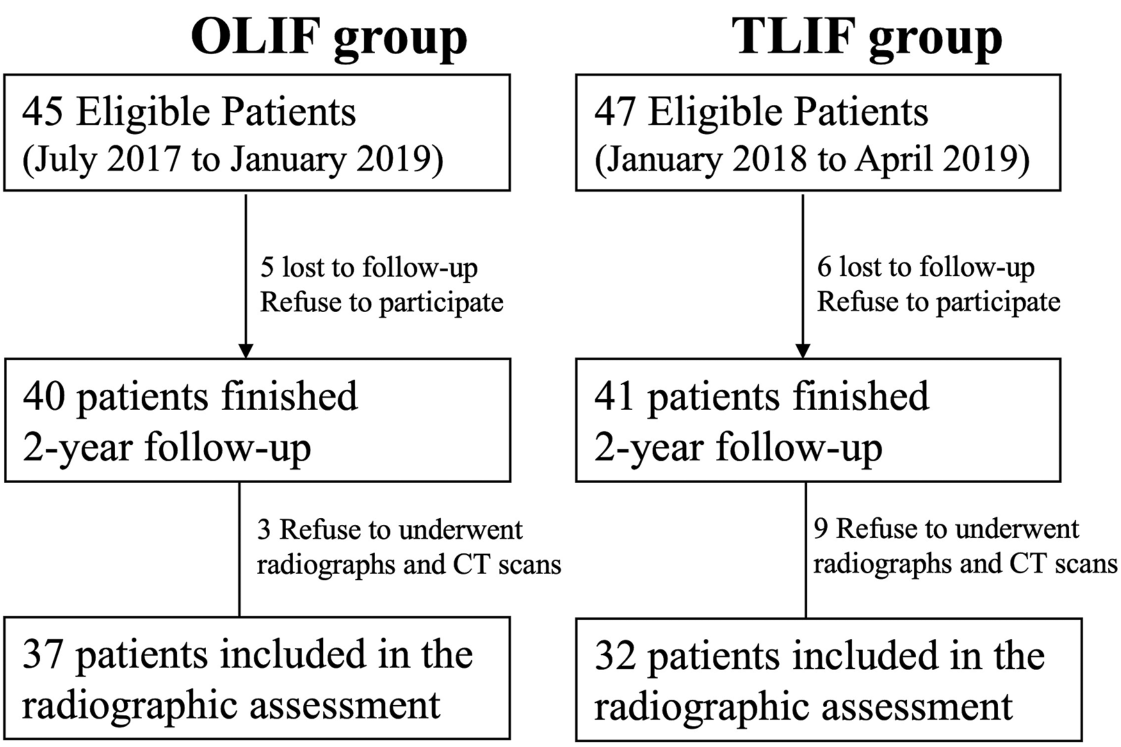

FIGURE 2
Enrollment and 2-year follow-up.

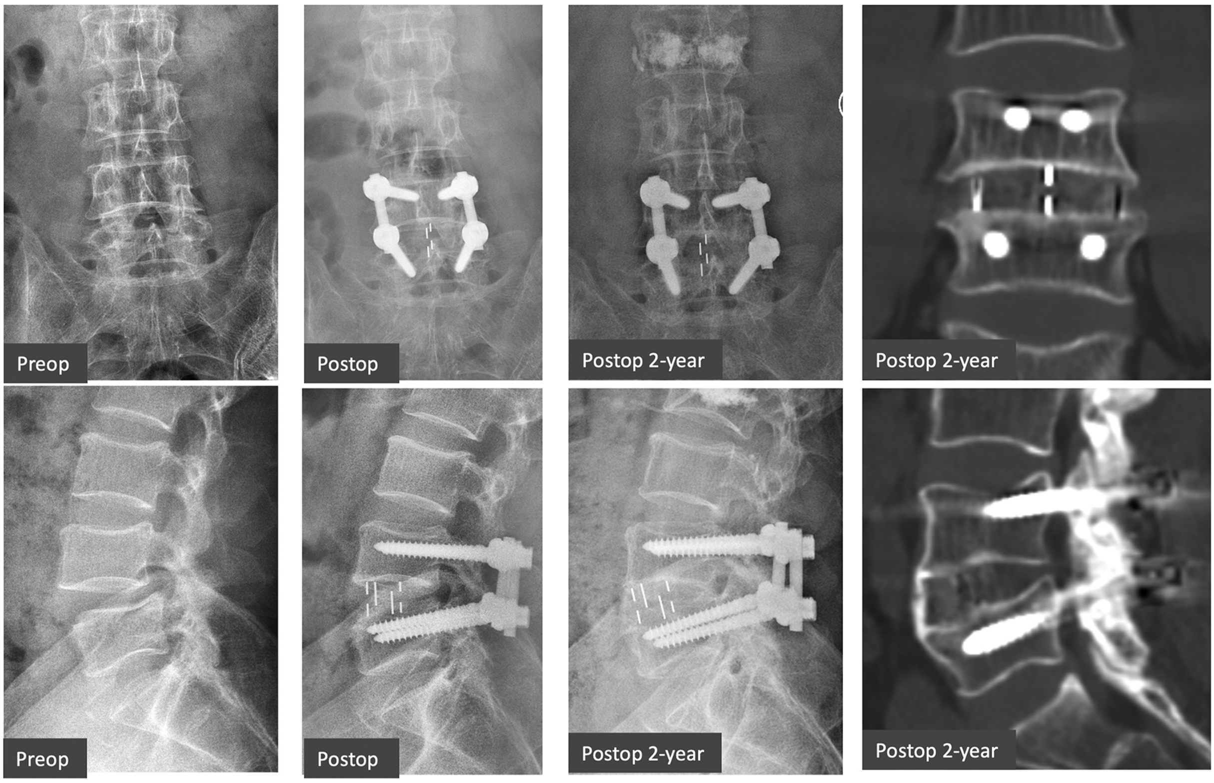

FIGURE 3
Case example of OLIF. A 63-year-old male patient with L4/5 degenerative spondylolisthesis had symptomatic low back pain and radiculopathy (ODI 35.6%, VAS-Leg 6, VAS-Back 6), which were relieved after OLIF with posterior laminotomy and fixation (ODI 10%, VAS-Leg 1, VAS-Back 2) at 2 years. Grade 1 fusion (apparent bone bridging) on CT scans was achieved at 2 years. OLIF, oblique lumbar interbody fusion; ODI, Oswestry disability index; VAS, visual analog scale.

Radiographic evaluations

Thirty-seven patients in OLIF group and 32 patients in TLIF were available for radiographic evaluation at 2 years after surgery (Table 4). Preoperative radiographic parameters, comprising disc height and segmental lordosis, showed similar results between two groups. Greater restoration of disc height obtained by OLIF (mean, 4.6 mm) than did TLIF (mean, 1.3 mm) at early postoperative period. The restoration of disc height at central, anterior, or posterior in OLIF group remained greater than those in TLIF group at 2 years. However, OLIF did not show greater restoration of segmental lordosis, compared with TLIF, at neither early postoperative period nor 2 years.

Both DH parameters and SL had minimal loss in both groups during 2-year follow-up and the magnitude of DH or SL loss had no significant difference between two groups.

Fusion status and complications

Fusion status and complications were shown in Table 5. Thirty-seven patients in OLIF group and 32 patients in TLIF were available for radiographic evaluation at 2 years after surgery. The fusion rates were 86.1% in TLIF group and 92.5% in OLIF group at 2 years, whereas there was no significant difference between two groups. For the implant-related complications, the rates of cage subsidence were different (TLIF, 38.9% vs. OLIF, 17.5%, $P = 0.037$). No differences were found in the rate of intraoperative endplate injury and vertebral fracture between two groups.

For the rates of neurological injury, no differences were found. Three patients suffered from permanent nerve root injury in TLIF group, while three patients had paresthesia over groin area but normal hip flexion power due to permanent lumbar plexus injury in OLIF group. In addition, five patients reported transient lumbar plexus injury in OLIF group, which were relieved within 3 months.

Two patients suffered from excessive bleeding (>1 L) during TLIF and underwent blood transfusion. One surgical site infection occurred in TLIF group and subsequent reoperation for debridement and lavage were performed. The rates of problematic complications, which comprised permanent nerve injury, excessive bleeding, non-fusion, or surgical site infection, were not different between two groups (OLIF, 12.5% vs. TLIF, 26.2%, $P = 0.118$), although there was a trend that TLIF had more problematic complication rate.

Discussion

Lower complication rates, less blood loss, and better corrective effect can be achieved by lateral approaches of interbody fusion for

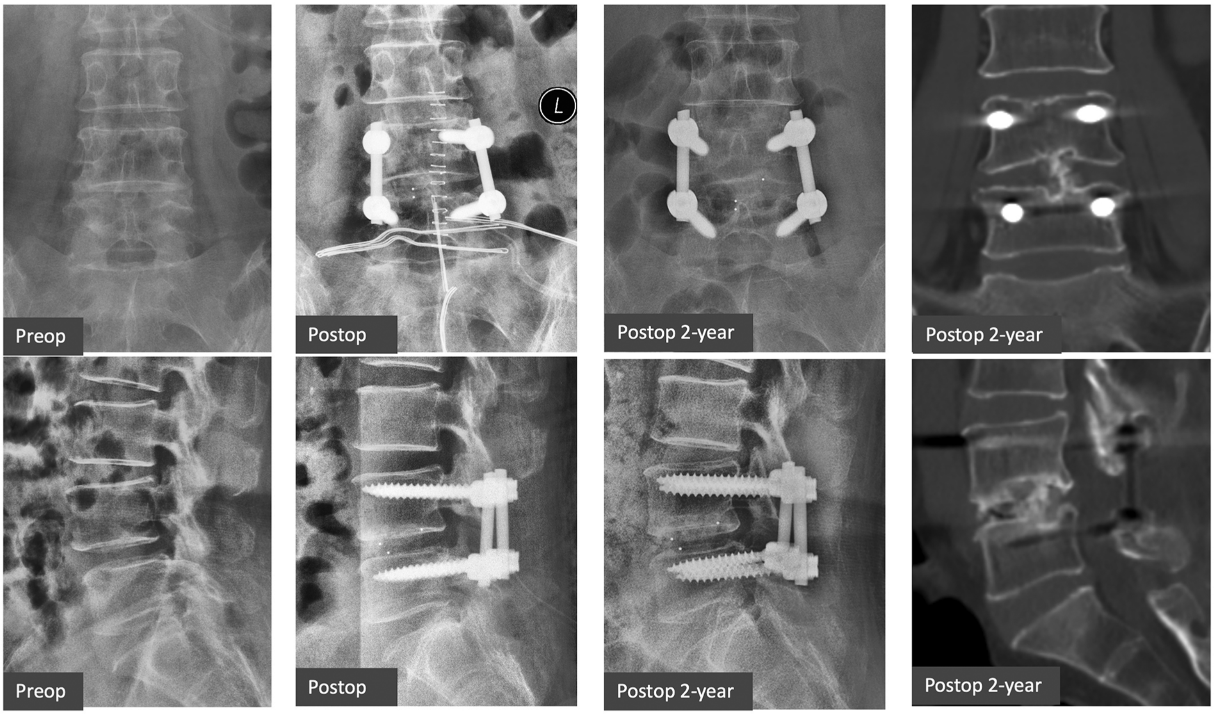

FIGURE 4
Case example of TLIF. A 56-year-old female patient with L4/5 degenerative spondylolisthesis had neurological claudication and low back pain (ODI 50%, VAS-Leg 5, VAS-Back 5). The symptoms were subsided after TLIF (ODI 16%, VAS-Leg 1, VAS-Back 2) at 2 years. Grade 2 fusion (patchy bone bridging) on CT scans was achieved at 2 years. TLIF, transforaminal lumbar interbody fusion; ODI, Oswestry disability index; VAS, visual analog scale.

deformity-correction surgery, compared with conventional TLIF (13). For degenerative spondylolisthesis, however, the benefit of OLIF was debated (14). Similar clinical outcomes and complication rates were shown in this prospective comparative study, although less blood loss, shorter hospital stay, higher disc height, and lower subsidence rates were shown in OLIF group than in TLIF group.

TABLE 1 Patient characteristics in OLIF and TLIF groups[a].

	TLIF	OLIF	*P*-value
Patients (*n*)	41	40	NA
Age (years)	61.2 ± 8.1	63.1 ± 8.2	0.311
Sex (female, %)	88%	75%	0.138
BMI (kg/m^2)	25.9 ± 3.9	26.3 ± 3.7	0.576
Slippage level (*n*)	45	43	
L3/4	5	6	0.687
L4/5	40	37	
Single	37	37	0.718
Two-level	4	3	
Fused segments (*n*)			
1	20	29	**0.029**
2	21	11	
Duration of operation (min)	157.0 ± 43.1	190.3 ± 40.3	**0.001**
Estimated blood loss	300 (300)	200 (100)	**<0.001**
>500 ml (*n*)	13	0	**<0.001**
>1,000 ml (*n*)	2	0	
Postoperative hospital stay (days)	5.5 ± 1.3	4.9 ± 1.1	**0.035**
Duration of follow-up (days)	763 ± 69	783 ± 79	0.948

OLIF, oblique lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion. Bold values mean *P*-value less than 0.05.
[a]Data presented as means and SDs if normal distribution was met, otherwise as median (interquartile range).

Clinical outcomes

The baseline characteristics were equivalent between two groups except for the proportion of two-level fusion and preoperative VAS-leg. The difference of VAS-leg between groups was only 0.8, not reaching clinically meaningful difference, which was regarded as comparable for two groups. Age (mean, 62.2 years), female proportion (82%), BMI (mean, 26.1 kg/m^2), preoperative ODI (mean, 45.6), VAS-back (mean, 4.5), and VAS-leg (mean, 5.3) for all patients with degenerative spondylolisthesis were similar to the baseline characteristics of previous studies (15–17).

As primary outcomes, the changes of VAS-back (OLIF, 2.5 vs. TLIF, 2.1), VAS-leg (OLIF, 3.4 vs. TLIF, 2.7), and ODI (OLIF, 26.8 vs. TLIF, 30) were similar between two groups at 2 years postoperatively, which suggested equivalent treatment effect on pain relief and functional improvements by these two different approaches of interbody fusion. OLIF did not show better clinical outcomes than did TLIF for single-level or two-level degenerative spondylolisthesis. These nonsignificant difference on treatment effect were consistent with two previous retrospective studies of 1-year follow-up (8, 9). Although the VAS and ODI in

TABLE 2 Comparisons of VAS and ODI between OLIF ($n = 40$) and TLIF ($n = 41$) groups[a].

	Preoperative			Postoperative 3-month			Postoperative month		
	OLIF	TLIF	*P*-value	OLIF	TLIF	*P*-value	OLIF	TLIF	*P*-value
VAS-back	4.8 ± 2.2	4.3 ± 1.6	0.289	3 (1)	2 (0)	0.003	3 (1)	2 (0)	**0.005**
VAS-leg	5.7 ± 1.9	4.9 ± 1.5	**0.041**	2 (1)	2 (0)	0.069	2 (1)	2 (1)	0.135
ODI	45.6 ± 16.6	45.7 ± 16.9	0.978	23.3 (13.1)	22 (14)	0.075	22 (15)	18 (13)	**0.041**
	Postoperative 1-year			Postoperative 2-year			Treatment effect at 2-year[b]		
	OLIF	TLIF	*P*-value	OLIF	TLIF	*P*-value	OLIF	TLIF	*P*-value
VAS-back	2 (1)	2 (0)	**0.024**	2 (1)	2 (1)	0.411	2.5 (1.8–3.2)	2.1 (1.6–2.6)	0.361
VAS-leg	2 (1)	2 (0)	0.218	2 (1)	2 (0)	0.226	3.4 (2.8–4.0)	2.7 (2.2–3.2)	0.095
ODI	20 (13)	18 (12.1)	0.099	19 (11.7)	14 (10)	0.069	26.8 (22–31.6)	30 (24.8–35.1)	0.367

OLIF, oblique lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion; VAS, visual analog scale; ODI, Oswestry disability index.
Bold values mean *P*-value less than 0.05.
[a]Data presented as mean and SD if normal distribution was met, otherwise as median (interquartile range).
[b]Treatment effect means the improvement of scores at 2 years, compared with preoperative scores. The values were presented with mean (95% confidential interval).

TABLE 3 Subgroup analysis of VAS and ODI between OLIF and TLIF groups[a].

	Preoperative			Treatment effect at 2 years[b]		
	OLIF	TLIF	*P*-value	OLIF	TLIF	*P*-value
Single-level fusion comparison (TLIF 20 cases vs. OLIF 29 cases)						
VAS-back	4.9 ± 2.4	4.4 ± 1.8	0.618	2.6 (1.7–3.5)	2.1 (1.3–2.8)	0.351
VAS-leg	5.9 ± 1.8	4.8 ± 1.7	0.027	3.6 (2.9–4.3)	2.5 (1.7–3.4)	**0.049**
ODI	46.1 ± 17	43.7 ± 16.4	0.618	26.3 (20.9–31.7)	28.1 (20.8–35.3)	0.791
Two-level fusion comparison (TLIF 21 cases vs. OLIF 11 cases)						
VAS-back	4.5 ± 1.7	4.3 ± 1.4	0.829	2.2 (1.2–3.2)	2.2 (1.6–2.8)	0.987
VAS-leg	5.0 ± 2.1	5.0 ± 1.3	1.000	2.8 (1.4–4.3)	2.9 (2.4–3.5)	0.903
ODI	44.3 ± 16.1	47.6 ± 17.5	0.607	28.1 (16.2–39.9)	31.8 (23.9–39.6)	0.572

OLIF, oblique lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion; VAS, visual analog scale; ODI, Oswestry disability index.
Bold values mean *P*-value less than 0.05.
[a]Data presented as mean and SD if normal distribution was met, otherwise as median (interquartile range).
[b]Treatment effect means the improvement of scores at 2-year, compared with preoperative scores. The values were presented with mean (95% confidential interval).

TABLE 4 Comparisons of radiographic parameters between OLIF and TLIF groups[a].

	Preoperative				Early postoperative (within 3 days)				Late postoperative (at 2 years)			
	DH	DHA	DHP	SL	DH	DHA	DHP	SL	DH	DHA	DHP	SL
TLIF	8.7 ± 1.9	10.6 ± 3.1	7.1 ± 1.9	12.9 ± 6.9	10.1 ± 1.8	12.4 ± 2.7	7.9 ± 1.9	14.4 ± 5.7	9.2 ± 2.1	11.2 ± 3.0	6.6 ± 1.8	12.7 ± 6.2
OLIF	8.3 ± 1.8	9.9 ± 2.5	6.8 ± 1.6	13.5 ± 7.6	13.0 ± 1.4	15.4 ± 2.2	9.9 ± 2.1	16.5 ± 7.3	11.8 ± 1.5	14.3 ± 2.3	8.4 ± 1.9	15.0 ± 7.4
P-value	0.378	0.270	0.460	0.732	**<0.001**	**<0.001**	**<0.001**	**0.154**	**<0.001**	**<0.001**	**<0.001**	0.137
	Changes from Preop[b]				Changes from Postop to 2-year follow-up[b]							
	DH	DHA	DHP	SL	DH	DHA	DHP	SL				
TLIF	1.3 ± 1.9	1.8 ± 2.5	0.8 ± 1.6	1.4 ± 5.4	0.8 ± 1.9	1.1 ± 2.3	1.2 ± 2.0	1.7 ± 3.7				
OLIF	4.6 ± 1.6	5.1 ± 2.4	3.1 ± 2.0	3.1 ± 5.5	1.2 ± 1.8	1.1 ± 2.5	1.4 ± 1.6	1.5 ± 2.9				
P-value	**<0.001**	**<0.001**	**<0.001**	0.209	0.471	0.910	0.551	0.807				

OLIF, oblique lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion; DH, disc height; DHA, anterior disc height; DHP, posterior disc height; SL, segmental lordosis.
Bold values mean *P*-value less than 0.05.
Totally 40 levels in OLIF group and 36 levels in TLIF were evaluated.
[a]Data presented as mean and SD if normal distribution was met, otherwise as median (interquartile range).
[b]Changes following operation means early postoperative values minus preoperative ones; changes following 2-year follow-up means late postoperative minus early postoperative ones.

both groups had statistically significant differences at 3-month, 6-month, and 1-year follow-up; however, the differences did not reach the clinically significant difference (18).

Given that TLIF group had higher proportion of two-level fusion (51.2% vs. 27.5% in OLIF group), subgroup analyses were performed and showed similar results. Only changes VAS-leg at 2-year revealed

TABLE 5 Fusion status and total complications at 2-year follow-up.

	TLIF	OLIF	*P*-value
Mechanical failure			
Endplate injury	12 (33.3%)	5 (12.5%)	0.111
Vertebral fracture	0	2 (5%)	
Cage subsidence	14 (38.9%)	7 (17.5%)	**0.037**
Grade 1	11 (30.6%)	7 (17.5%)	
Grade 2	3 (8.3%)	0	
Non-fusion	5 (13.9%)	3 (7.5%)	
Class 1 (fused)	10	11	0.365
Class 2 (fused)	21	26	
Class 3 (not fused)	4	3	
Class 4 (not fused)	1	0	
Neurological injury			
Transient numbness or pain	0	6 (15%)	0.096
Permanent paresthesia	3 (7.3%)	2 (5%)	
Permanent motor deficit	0	0	
Others			
Excessive bleeding	2 (4.8%)		
Surgical site infection	1 (2.4%)		
Total problematic complications[a]	11 (26.2%)	5(12.5%)	0.118

OLIF, oblique lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion.
Bold values mean *P*-value less than 0.05.
[a]Includes permanent nerve injury, excessive bleeding, non-fusion, surgical site infection.

significant difference (OLIF, 3.6 vs. TLIF, 2.5) in single-level subgroup comparison, whereas the preoperative VAS-leg was not equal (OLIF: 5.9 vs. TLIF: 4.8), indicating the greater treatment effect of VAS-leg in OLIF group was created by greater preoperative VAS-leg.

Fusion status and complications

Cage subsidence occurred at seven levels in OLIF group (17.5%), which were all Grade 1 (25%–50% subsidence). Previous study of lateral lumbar interbody fusion reported similar cage subsidence rate of 10% at 1-year follow-up by Malham et al. (19). In contrast, 14 levels (38.9%) in TLIF group had cage subsidence among those three levels had Grade 2 (50%–75% subsidence), which was close to 34.1% occurrence in the study by Yao et al. (20). Lower cage subsidence rate in OLIF group suggested anteriorly placed large-size cages with posterior fixation provide more stable construct than those in TLIF group.

The fusion rates of two groups in this study were compatible with previous systematic reviews (OLIF, 90.1% vs. TLIF, 87.1%) (19, 21). Allograft with demineralized bone matrix together with large-size cages were implanted in OLIF group, compared with morselized cancellous bone graft in bullet-shaped cages in TLIF group. With less cage subsidence, however, OLIF group did not have significantly higher fusion rate than did TLIF group (OLIF, 92.5% vs. TLIF, 86.1%), although the trend of higher fusion rate existed.

Abe et al. (22) reported 13.5% of 155 patients who underwent OLIF presented with transient neurological deficit, whereas only 1.2% permanent. In this study, six patients (12.5%) in OLIF group had transient paresthesia over groin area or psoas weakness, which were subsided until three months postoperatively. However, two patients (5%) had permanent paresthesia over groin area without motor deficit, which had relatively higher occurrence than did another study (reporting 2.6% permanent paresthesia) (23). Higher rate of paresthesia over groin area in this study probably caused by manipulation of the anterior portion of psoas (Zone 1), resulting in genitofemoral nerve injury (24). In contrast, three patients (7.3%) suffered from permanent paresthesia over lower limb without motor deficit in TLIF group.

The total problematic complications rates were similar between two groups, although there was a trend of lower complication rate in OLIF group (12.5% vs. TLIF, 26.2%). In TLIF group, unexpected excessive blood loss (>1,000 ml) occurred in two patients and surgical site infection occurred once.

Radiographic parameters

Large-size cage with lordotic angle was used in OLIF, which greatly enlarge the intervertebral space with respect of disc height and segmental lordosis. Previous studies have proved the correction effect by lateral approach of interbody fusion, especially for spinal deformities. In this study, OLIF showed better improvement of disc height than did TLIF (OLIF, 4.6 mm vs. TLIF, 1.3 mm). Consistence results between two groups were also shown for disc height in previous retrospective comparative studies (7–9).

However, the improvement segmental lordosis between two groups showed inconsistent results, compared with previous studies. In this study, the improvement segmental lordosis was similar between two groups (OLIF: 3.1° vs. TLIF: 1.4°), similar to 2.8° changes in previous study of Lateral Lumbar Interbody Fusion (LLIF) (25). For degenerative spondylolisthesis, the local deformity is not severe. With slight loss of preoperative segmental lordosis (mean preoperative SL: 13.2°), the magnitude of angular correction by OLIF was limited.

Limitations

Heterogeneity occurred in the comparison between two groups. The different proportions of two-level fusion existed, and the following subgroup analysis showed similar results to the whole group comparisons. However, the sample size in subgroups was decreased, which probably impaired the power of statistics to detect the group difference. In this study, heterogeneity also exited in techniques of OLIF. Half of patients underwent OLIF with direct decompression which means partial laminectomy through posterior midline approach. Hence, subgroup of OLIF without direct decompression (minimally invasive technique) was compared with TLIF group.

Similarly, no differences were found in terms of pain relief and functional improvement.

This study was conducted in a single center. Although techniques of procedure and patient characteristics were similar to previous studies, differences may exist and may impact on the external validity of the result of this study.

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 Beijing Jishuitan Hospital ethics committee. The patients/participants provided their written informed consent to participate in this study.

Author contributions

JW collected, analyzed, and interpreted the data and wrote the draft. YS, YW, and XT performed the surgery, designed the protocol, and revised the draft. JA, ZX, GL, and TG measured the radiographic parameters and followed up with the patients. 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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The use of a novel reduction plate in transoral anterior C1-ring osteosynthesis for unstable atlas fractures

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Background: Transoral anterior C1-ring osteosynthesis has been reported as an effective treatment for unstable atlas fracture, which aims to preserve important C1–C2 motion. However, previous studies have shown that the anterior fixation plates used in this technique were not suitable for the anterior anatomy of the atlas and lacked an intraoperative reduction mechanism.
Objective: This study aims to evaluate the clinical effects of a novel reduction plate used in transoral anterior C1-ring osteosynthesis for unstable atlas fractures.
Methods: 30 patients with unstable atlas fractures treated by this technique from June 2011 to June 2016 were included in this study. The patients' clinical data and radiographs were reviewed, and the reduction of the fracture, internal fixation placement, and bone fusion were assessed using pre- and postoperative images. The patients' neurological function, rotatory range of motion, and pain levels were evaluated clinically during follow-up.
Results: All 30 surgeries were successfully performed, and the average follow-up duration was 23.5 ± 9.5 months (range 9–48 months). One patient suffered atlantoaxial instability during the follow-up and was treated with posterior atlantoaxial fusion. The remaining 29 patients had satisfactory clinical outcomes, with ideal fracture reduction, good screw and plate placement, well-preserved range of motion, neck pain alleviation and solid bone fusion. There were no vascular or neurological complications during the operation or follow-up.
Conclusions: The use of this novel reduction plate in transoral anterior C1-ring osteosynthesis is a safe and effective surgical option in the treatment of unstable atlas fractures. This technique offers an immediate intraoperative reduction mechanism, which provides satisfactory fracture reduction, bone fusion, and preservation of C1–C2 motion.

KEYWORDS

transoral approach, unstable atlas fracture, open reduction, internal fixation, atlantal plate

Introduction

Atlas fractures comprise a proportion of craniocervical injuries, acute cervical spine fractures, and all spine fractures, accounting for 25%, 2%–13%, and 1%–2%, respectively (1, 2). These fractures commonly occur at the weakest point of the atlas, which coincides with the attachment of the anterior and posterior arch in the lateral mass. Sköld's study has indicated that forehead injuries associated with extension generally cause posterior arch fractures, while axial compression due to an impact on the vertex is associated with anterior and posterior arch fractures (3).

Several classification systems for atlas fractures have been proposed. The most commonly used classifications in clinical research are the Jefferson, Landells and Van Peteghem, and Gehweiler classifications (4). The Gehweiler classification, which integrates categories from previous classifications, is considered more useful for clinical treatment (5). In prior literature, the presence or absence of injury to the transverse ligament (TAL) has been used to determine the stability of atlas fractures. Lee and Woodring's retrospective analysis of a large number of patients with atlas fractures suggests that single anterior arch fractures and posterior arch fractures without transverse ligament injury may be stable fractures, while other types are unstable fractures (6).

The optimal treatment for unstable atlas fractures remains a topic of debate, with no consensus on whether surgical or nonsurgical treatment is preferable. Nonsurgical treatments of unstable atlas fractures have been associated with poor reduction and high rates of nonunion, and neurological damage caused by instability of C0–C2 (7). Although posterior C1–C2 or C0–C2 fusion surgery can achieve satisfactory stability and bone fusion, it results in the loss of rotation of C1–C2 and flexion-extension of C0–C1 (8). In contrast, C1-ring osteosynthesis is an effective alternative to posterior C1–C2 or C0–C2 fusion for treating unstable atlas fractures while preserving important C1–C2 motion (2). Previous studies have reported on transoral anterior C1-ring osteosynthesis, but the anterior fixed plates used were not suitable for the anterior anatomy of the atlas and lacked an intraoperative reduction mechanism (9, 10).

This report presents a retrospective analysis of 30 patients with unstable atlas fracture treated using a novel reduction plate (**Figure 1**, Wego, Shangdong, China) for transoral anterior C1-ring osteosynthesis, and evaluates the preliminary clinical effects of this technique.

Materials and methods

Patients

This study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee (IRB:20210033), with informed written consent obtained from each patient. From June 2011 to June 2016, a consecutive series of 30 patients with unstable atlas fractures were recruited and treated by transoral anterior C1-ring osteosynthesis using a novel reduction plate (**Table 1**). Prior to surgery, all patients underwent routine preoperative anteroposterior, open-mouth and lateral radiographs, computed tomography (CT), and magnetic resonance imaging (MRI).

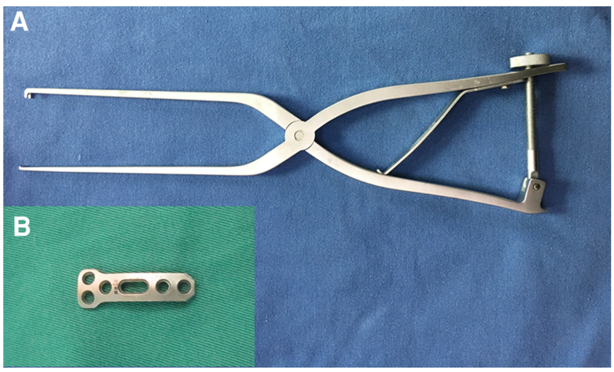

FIGURE 1
Novel instruments. (A) The reduction forceps. (B) The reduction plate.

Surgical procedure

Preoperative preparation: Prior to surgery, patients were required to gargle six times daily with vinegar chlorhexidine, and underwent a professional dental cleaning. Intravenous ceftriaxone and ornidazole antibiotics were administered 30 min prior to the operation, and a nasogastric feeding tube was inserted.

Surgical technique: Under general anesthesia via nasal cannula, patients were positioned supine, and the oropharynx was cleaned and disinfected. The median posterior pharyngeal wall was then longitudinally incised about 3–4 cm to expose the anterior arch and lateral mass of the atlas. After verifying the location of the fracture, an appropriately sized plate was placed in front of the atlas. For a single fracture in the anterior arch, the wide end of the plate was fixed to the lateral mass near the fracture gap using two 18–26 mm screws. A temporary reduction screw was inserted into the anterior arch through the sliding hole of the plate. After C-arm fluoroscopy confirmed the position of the implanted device, a reduction forceps (**Figure 1A**) was installed between the reduction hole and temporary reduction screw. The forceps handles were then closed to apply compression force to close the fracture gap (**Figure 2A**). After confirming fracture reduction under direct vision, another two screws were placed in the atlas to fix the other end of the plate (**Figure 2B**), and the temporary reduction screw was removed (**Figure 2C**). For a double fracture in the anterior arch, a Crutchfield clamp was used to compress the lateral masses inwards to achieve fracture reduction (9), and then an appropriately sized plate was placed in front of the atlas to fix the fractures directly. C-arm fluoroscopic imaging was used to verify the location of the plate and screws, and the incision was closed in the muscular and mucosal layers.

Postoperative management and follow-up

Postoperatively, patients had their tracheal cannula removed after 24–48 h, and nasogastric feeding tube removed after 7 days. Ultrasonic nebulisation and 0.02% chlorhexidine acetate gargling were administered 3–5 times daily for 7 days, and intravenous ceftriaxone and ornidazole antibiotics were given for 3 days. Cervical radiographs and CT scans were obtained 3 days after surgery to assess fracture reduction and the placement of fixation, as well as total lateral mass displacement (LMD). Patients were required to wear a rigid Philadelphia cervical collar for one month. Follow-up occurred at 3, 6, 9, and 12 months,

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TABLE 1 Clinical data of 30 patients.

Case	Gender	Age (years)	Injury cause	Fracture type	LMD (preop)	LMD (postop)	VAS (preop)	VAS (postop)	Bone fusion confirmed (month)	Follow-up (month)	Complications
1	F	40	Falling	III	6.1	0.0	5	1	3	12	No
2	M	42	MVA	III	5.5	0.0	8	1	3	36	No
3	M	66	MVA	III	6.1	1.7	7	1	6	36	No
4	M	24	Falling	III	6.5	2.5	8	2	6	48	No
5	M	52	MVA	III	12.3	2.5	6	1	9	24	No
6	F	26	Falling	III	7.2	0.0	7	1	3	24	No
7	F	42	Falling	III	4.3	0.0	8	2	3	24	No
8	M	28	MVA	III	6.5	0.0	6	1	3	12	No
9	M	65	Crushing	III	6.4	3.3	4	0	6	9	No
10	M	38	Falling	III	8.7	0.0	7	2	3	15	No
11	F	32	MVA	III	4.0	0.0	6	1	3	18	No
12	F	49	Falling	III	7.3	0.0	7	2	6	24	No
13	M	62	Falling	III	9.3	0.0	6	1	3	24	No
14	F	23	MVA	III	5.0	0.0	7	1	3	36	No
15	M	53	MVA	III	4.9	0.0	6	2	3	30	No
16	M	41	Crushing	III	6.4	0.0	8	1	3	24	No
17	F	47	MVA	III	6.6	2.0	7	2	6	12	Instability
18	M	58	MVA	III	4.8	0.0	8	2	3	24	No
19	M	47	Falling	III	8.1	0.0	6	1	3	36	No
20	M	45	MVA	III	7.2	1.5	8	1	6	24	No
21	F	43	Crushing	III	4.0	0.0	7	1	3	12	No
22	M	61	MVA	III	5.0	0.0	6	1	3	36	No
23	F	32	Crushing	III	6.2	0.0	7	2	3	12	No
24	F	53	Falling	III	4.0	2.5	8	3	9	18	No
25	F	66	MVA	III	4.7	0.0	7	2	3	30	No
26	M	51	MVA	III	5.2	1.9	8	2	6	21	No
27	M	41	Falling	III	12.4	3.6	6	1	9	24	No
28	M	41	Crushing	III	4.5	0.0	7	1	3	12	No
29	M	47	Falling	III	5.0	0.0	8	2	3	24	No
30	F	21	MVA	III	9.1	1.5	7	1	6	24	No
M ± SD					6.4 ± 2.2	0.8 ± 1.2	6.9 ± 1.0	1.4 ± 0.6			
t					15.739	36.546					
P					0.000*	0.000*					

M, male; F, female; MVA, motor verhicle accident; LMD, lateral mass displacement; VAS, visual analog scale.
*Paired-sample *t*-test.

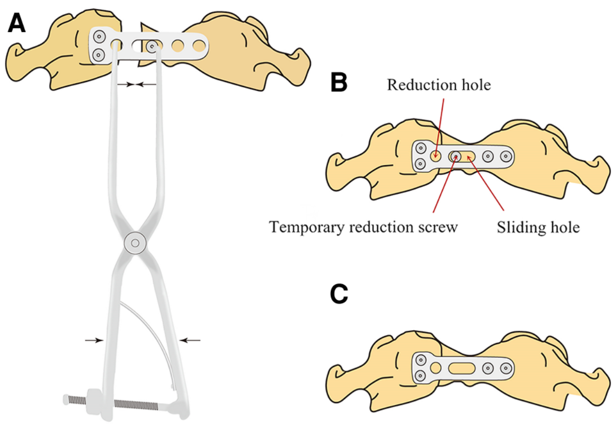

FIGURE 2
Reduction schematics of the novel plate for atlas fractures. (A) The forceps handles were closed to impart a compression force to reset the fracture after placement of the plate and temporary reduction screw. (B) Reduction of the fracture was achieved, and the plate was completely fixed. (C) The temporary reduction screw was removed.

and then once per year or as needed. Neck pain was assessed by visual analog scale (VAS), and the neurological status was also evaluated using the Japanese Orthopaedic Association (JOA) score (17-point system). Cervical radiographs and CT scans were performed at each follow-up to evaluate bone fusion of the fractures.

Statistical analysis

The present study employed the Kolmogorov-Smirnov test to assess the normal distribution of the data, which were subsequently reported as mean and standard deviation. The statistical analysis of the data was performed using the paired-samples *t*-test and was conducted using SPSS 21.0 software (IBM, Armonk, NY, USA). A significance level of $p < 0.05$ was deemed appropriate to determine the statistical significance of the results.

Results

Characteristics of the study population

The study population consisted of 30 patients, comprising 18 men and 12 women with a mean age of 44.5 years (range 21–66 years). The causes of injury were falling (11 cases), motor vehicle accident (14 cases), and crushing (5 cases). All patients presented with neck pain and restricted motion of the cervical spine without neurological symptoms. Additionally, all patients had a JOA score of 17. In 9 cases, the fractures had failed to unite by using primary conservative treatment for 3 to 6 months, which included occiputocervicothoracic cast in 5 cases, rigid collar in 3 cases, and halo-vest in 1 case. The combined fractures of the anterior and posterior atlantal arches were found on CT images in all cases in this study, which were classified as type III fractures according to Gehweiler classification system (5). 9 patients had Dickman type I transverse atlantal ligament (TAL) injury (disruption of the midportion of the transverse was found on MRI), while Dickman type II TAL injury (fractures or bony avulsion at the attachment site of TAL presented on CT images) (11) was presented in 13 cases.

Surgical results

All 30 surgeries were performed successfully without any neurovascular injury. The mean operative time was 78.3 ± 17.0 min (range 55–110 min), with an average intraoperative blood loss of 54.0 ± 22.2 ml (range 20–100 ml).

Radiological results

Postoperative CT scan revealed that plates and screws were well-placed in all cases (**Figure 3**), and the postoperative LMD (0.8 ± 1.2 mm, range 0.0–3.6 mm) significantly decreased compared to preoperative LMD (6.4 ± 2.2 mm, range 4.0–12.4 mm) ($p < 0.01$). None of the patients had screw or plate loosening or breakage after CT scans and plain radiographs during the follow-up period. One patient exhibited atlantoaxial instability (anterior atlanto-dental interval greater than 3 mm in flexion) during dynamic cervical radiograph 9 months after surgery and underwent posterior atlantoaxial fusion revision surgery. All other 29 cases had successful bone fusion after 3–9 months, with the patient who underwent revision surgery achieving bone fusion 6 months post revision surgery (**Table 1**). The postoperative cervical rotatory range of motion of the 29 patients was 48.9° ± 10.6° with a range of 35.8°–65.3°. All 29 patients had well-preserved range of motion.

Clinical results

The 29 patients were followed up for a period ranging from 9 to 48 months, with an average of 23.5 ± 9.5 months, while the patient who underwent revised surgery was followed-up for 12 months. All patients maintained similar neurological functions to preoperative levels, with a JOA score of 17. The preoperative VAS scores (6.9 ± 1.0; range 4–8) were significantly reduced (1.4 ± 0.6; range 0–3; $p < 0.01$) after surgery. No complications of infection were observed as complications.

Discussion

The atlas, also known as the first cervical vertebra, is a ring-shaped structure formed by the anterior and posterior arches and the two lateral masses without a vertebral body and spinous process. The regions where the anterior and posterior arches connect with the lateral masses are relatively thin and represent the weakest points of the atlantal ring. As a result of this unique

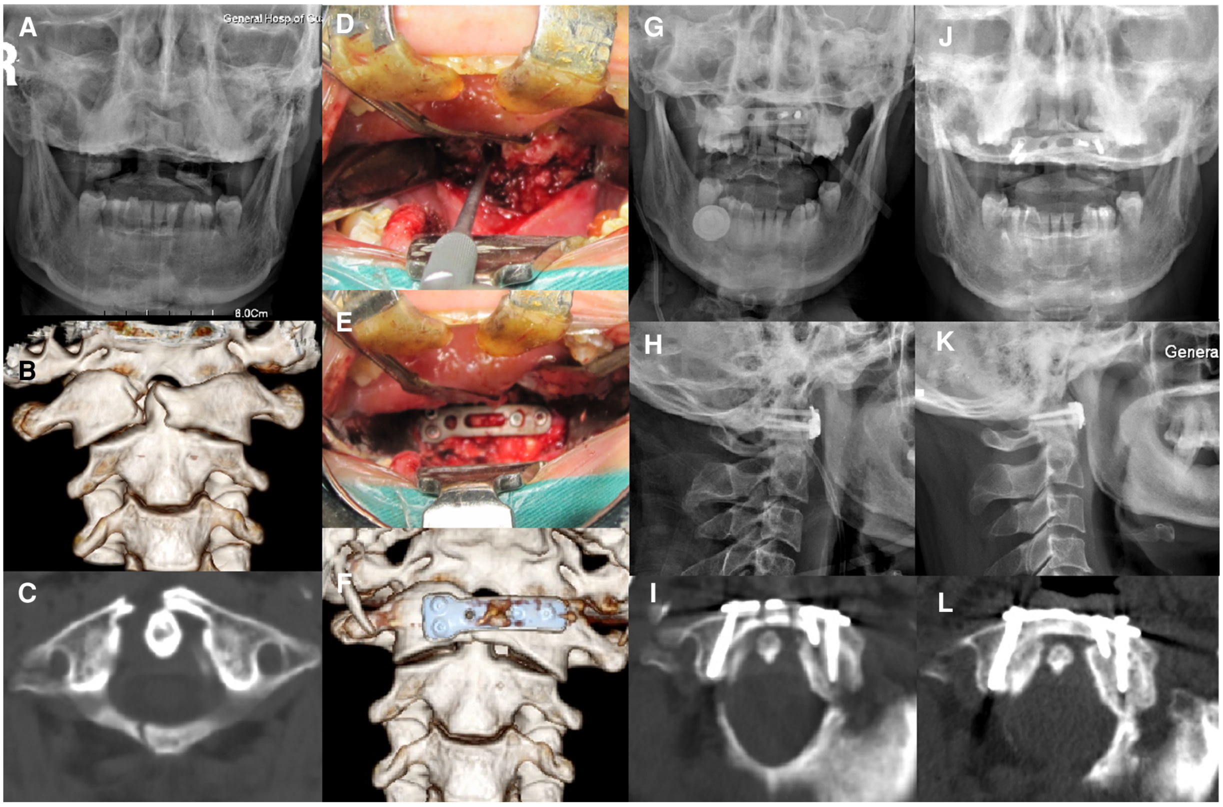

FIGURE 3
A 47-year-old female with combined fractures of the anterior and posterior atlantal arches was treated by transoral anterior C1-ring osteosynthesis using the novel reduction plate. (A) Preoperative open-mouth x-ray imaging showed displacement of the lateral masses. (B,C) The reconstructed images in the coronal and axial CT scan revealed fractures through the right side of the anterior and posterior arches of the atlas with displacement of the lateral mass. (D,E). Intraoperative photographs of an anterior arch fracture before and after fixation. (F) The reconstructed images after surgery showed optimal plate location. (G,H). Postoperative open-mouth and lateral x-ray imaging identified the relatively good C1–C2 alignment. (I) An axial CT image after surgery revealed reduction of the anterior arch fracture and adequate screw placement. (J,K) Open-mouth and lateral x-ray images at 6 months after surgery showed no loosening of the plate or screws. (L) An axial CT image at 6 months after surgery revealed solid bone fusion.

anatomy, the atlas is most commonly fractured with two or more breaks in the ring structure (12). The stability of atlas fractures was traditionally determined by the structural integrity of the TAL (2). However, recent studies have shown that combined fractures of the anterior and posterior atlantal arches are unstable, regardless of the TAL involvement (6, 10, 13).

Patients with atlas fracture rarely present symptoms of neurological dysfunction, as there is an increase of the space available for the spinal cord after fractures of the atlantal ring, thereby preventing compression. While quadriplegia and hemiparesis may occur for a few minutes, these episodes generally fade away rapidly (14). Therefore, stabilization of fractures is the most important factor in the treatment of atlas fractures. While there is agreement on the treatment of stable atlas fractures, the optimal management of unstable atlas fractures remains controversial. Non-operative treatments such as skull traction and external immobilization using halo-vest or occiputocervicothoracic cast or rigid collar have been commonly suggested in the past (15). Although satisfactory outcomes could be obtained in most patients without associated neurologic deficits after nonoperative treatments, there is a high risk of nonunion (7). Mechanical instability and incongruence of the atlanto-occipital and the atlanto-axial joints may lead to arthrosis, persistent neck pain, and even neurologic injury. Dvorak et al. (16) reported that conservative treatments for atlas burst fractures failed to restore patients to their preoperative functional levels and suggested that nonoperative treatments were not optimal. Moreover, immobilization of the cervical spine for several months may lead to significant discomfort and other complications especially in elderly patients (17).

C1–C2 or C0–C2 fixation and fusion techniques, including C1–C2 transarticular screw fixation, C1–C2 screw-rod fixation, and occipitocervical plate-screw-rod fixation, are commonly used in surgical stabilization for unstable atlas fractures (18, 19, 20). These fixation techniques offer adequate biomechanical stability to achieve a high fusion rate (21, 22). However, they have certain limitations, such as loss of normal motion of the C1–C2 and C0–C1 joints and possible increased incidence of subaxial cervical spine degeneration (2).

In 2004, Ruf et al. (23) reported a transoral anterior C1-ring osteosynthesis technique that uses a lateral mass screw-rod construct to stabilize unstable atlas fractures while preserving C1–C2 motion, and obtained satisfactory clinical outcomes. Dickman proposed that the rupture of TAL results in permanent anterior instability of the C1–C2 joint (24). Alves et al. (5) recommended using C1-ring osteosynthesis to treat Gehweiler Type IIIb atlas fractures (combined injury of the anterior and posterior arch of the atlas with TAL damage) with a Dickman type II TAL injury. Kandziora et al. (4) suggested that Gehweiler Type IIIb atlas fractures with midsubstance ligamentous disruption (Dickman type I) or severely dislocated ligamentous bony avulsions (Dickman type II) of the TAL should be treated by C1–C2 fusion, while Gehweiler Type IIIb atlas fractures with moderately dislocated ligamentous bony avulsion (Dickman type II) of the TAL may be treated by C1-ring osteosynthesis only. However, recent biomechanical researches have suggested that under physiologic loads, solitary C1 fixation can provide adequate stabilization, and the well-preserved longitudinal ligaments have sufficient capacity to maintain the stability of the C1–C2 joint even with concomitant TAL injuries in atlas fractures (25, 26). A retrospective clinical study form Shatsky et al. (27) suggested that C1-ring osteosynthesis can be performed in the setting of incompetent TAL regardless of TAL injury type without resulting in C1–C2 instability. C1-ring osteosynthesis is currently considered a valid alternative to posterior C1–C2 or C0–C2 fusion for unstable atlas fractures, with or without TAL injury.

C1-ring osteosynthesis could be performed by either a transoral anterior or posterior approach (2, 9, 10, 27). Reduction of anterior arch fractures is critical, as the healing of anterior arch is essential to restore atlantoaxial stability. Although the transverse screw-rod fixation could be used for compression reduction in posterior C1-ring osteosynthesis, the compression force only directly acts on the tail of the screws, and the force transferred to the front end of the screws is insufficient, leading to poor reduction of anterior arch fractures. A transoral anterior approach provides direct access to the anterior arch of the atlas, enabling optimal closure of anterior arch fractures under direct vision.

Previous studies have reported satisfactory effects for unstable atlas fractures using transoral anterior C1-ring osteosynthesis. However, these instruments were not perfectly suited to the anterior anatomy of the atlas according to a lateral mass screw-rod construct used by Ruf et al. (23) and a reconstruction plate used by Ma et al. and Hu et al. (9, 10). Therefore, a novel C1 anterior plate with a reduction mechanism was developed by our team for transoral anterior C1-ring osteosynthesis in unstable atlas fracture that can preserve normal C1–C2 rotatory motion.

In this study, we evaluated the clinical efficacy and safety of a novel reduction plate instrumentation technique in the treatment of unstable atlas fractures. A total of 30 patients with unstable atlas fractures were included in the study, and clinical efficacy and safety were evaluated on follow-up. One patient in the study had C1–C2 instability, which was corrected by posterior C1–C2 fusion. The remaining 29 patients achieved a well-preserved range of motion and satisfactory bone fusion without signs of instability or complications. The failure case was attributed to a possible obscure damage of other ligaments. This novel reduction plate instrumentation unified the burst fracture by compression forces using a configured reduction forceps. Wound infection may be a matter of concern during the transoral approach. With proper preoperative preparation and postoperative care, the complication rate can be markedly reduced (28). No wound infection occurred in our case series.

Limitations

There are several limitations in this study. Firstly, the sample size is relatively small, which may limit the generalizability of the findings. Further studies with larger sample sizes are necessary to fully evaluate the safety and efficacy of this technique. Additionally, as this is a retrospective study, it is subject to potential biases and limitations inherent in this type of study design. A prospective study with standardized outcome measures and controlled follow-up intervals may provide more robust results. Furthermore, the lack of a control group in this study limits the ability to comprehensively evaluate the effects of this technique.

Conclusion

Transoral anterior C1-ring osteosynthesis using this novel reduction plate is a safe and effective surgical option to manage unstable atlas fractures. This technique can provide satisfactory reduction, optimal stabilization and bone fusion of fracture, and preserve important C1–C2 motion.

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 General Hospital of Southern Theatre Command of PLA. The patients/participants provided their written informed consent to participate in this study.

Author contributions

XZ: Conceptualization, Methodology, Writing—Original Draft. HY: Conceptualization, Methodology. SF: Conceptualization, Methodology. CD: Validation, Formal analysis. JC: Validation, Formal analysis. RM: Software, Visualization. XM: Writing-Review & Editing. HX, XZ: Conceptualization, Methodology, Writing-Review & Editing. 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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