Open Access

CLINICAL ARTICLE

Bone-to-Bone Ligament Preserving Laminoplasty with Ultrasonic Osteotome Assistance for Intraspinal Tumors: A Technical Note and Clinical Follow-Up

Hongtao Rong, MD, Sipeng Li, MD, Ruiguang Zhang, MM, Bowen Zheng, MM, Yuhang Diao, MD, Tao Zhu, MD, PhD

Department of Neurosurgery, Tianjin Medical University General Hospital, Tianjin, China

Objective: Laminectomy has been widely used for intraspinal tumor resection. However, the tilted spinous process and narrow lateral laminae of the thoracic spine along with the hypertrophic ligamentum flavum of the lumbar spine pose certain problems for the laminae removal of the traditional laminectomy. We improved the laminectomy method with ultrasonic osteotome to treat thoracolumbar tumors and assessed its safety and superiority.

Methods: A retrospective analysis was performed in 86 patients with thoracolumbar (T4–L5) spinal tumors treated by resection, including 44 with the lamina removed using the traditional method and 42 with the lamina removed using the bone-to-bone ligament preserving (BLP) laminoplasty, which preserves the posterior ligament complex. Age, sex, and tumor size, location, and depth were compared between the two groups. The length of incision and bone window, time to remove the vertebral lamina, and epidural effusion volume were recorded at 2 weeks after surgery in the two groups. Postoperative reexamination by magnetic resonance imaging (MRI) at 2 weeks and 3 months after surgery was compared with preoperative MRI to assess the change in vertebral lamina displacement.

Results: There were no statistical differences in age, sex, and tumor size, depth, or location between the two groups. The BLP laminectomy did not increase the risk of dural, spinal cord, or nerve injuries. The difference between the incision and tumor length, as well as the difference between the bone window and tumor length in the BLP laminectomy group, were smaller than those in the traditional laminectomy group, and the BLP laminectomy took less time compared to that of the traditional laminectomy ($p < 0.05$). There was no significant difference in the volume of epidural effusion between the two groups at 2 weeks postoperatively, or in the displacement of the returned vertebral plate observed in sagittal and axial positions. The same was true for the displacement at 3 months postoperatively in the axial position. However, the sagittal displacement in the BLP laminectomy group was smaller than that in the traditional laminectomy group ($p < 0.05$).

Conclusions: The BLP laminectomy is safe for the resection of thoracolumbar spinal canal tumors. It is less traumatic and faster, with less displacement of the returned lamina, resulting in a stable repair of the spine.

Key words: Bone-To-Bone Ligament Preserving (BLP) Laminoplasty; Safety; Superiority; Thoracolumbar Spinal Tumors; Ultrasonic Osteotome-Assisted

Address for correspondence Tao Zhu, MD, PhD, Department of Neurosurgery, Tianjin Medical University General Hospital, No. 154 Anshan Road, Heping District, Tianjin, China 300052; Fax:+8602260814488; Tel: +8602260814488; Email: zhutao5@126.com
Hongtao Rong, Sipeng Li, and Ruiguang Zhang contributed equally to this work and share first authorship.
Grant sources: All authors acknowledge hereby that they meet the authorship criteria according to the latest guidelines of the International Committee of Medical Journal Editors and that they are in agreement with the manuscript.
Disclosure: The authors declare no conflict of interest about this study.
Received 17 November 2022; accepted 20 March 2023

Orthopaedic Surgery

Introduction

Primary intraspinal tumors account for 2%–15% of all central nervous system tumors, and approximately 40% of intraspinal tumors occur in the dura mater. Because most subdural tumors have clear boundaries and are benign, early surgery is the first choice for treatment, and radical resection can usually achieve a curative effect.[1] Laminectomy with bone grafting has been widely used for intraspinal tumor resection. Although factors such as patient age, surgical location, and type of lesion contribute to a wide variation of spinal deformities after surgery, as reported in the literature,[2] there is a consensus that laminoplasty can better restore spinal stability, reduce the risk of medically induced deformity, and facilitate re-operative manipulation.[3]

The traditional method of removing the lamina is to cut off both sides of the lamina and further remove the supraspinal ligament, interspinous ligament, and ligamentum flavum; however, the tilted spinous process and narrow lateral laminae of the thoracic spine as well as the hypertrophic ligamentum flavum of the lumbar spine bring some difficulties for the removal of the laminae. With the widespread use of ultrasonic osteotomes in spinal surgery, the vertebral plate can be removed more conveniently. We adopted a novel technique—bone-to-bone ligament preserving (BLP) laminoplasty technique—for the removal of the laminae in cases of intravertebral tumors in the thoracolumbar segment and experienced many advantages with this technique, the methodology of which is described herein.

The key features of this BLP laminectomy include cutting the vertebral lamina laterally according to the length of the tumor, avoiding overexposure of the incision and bone window, and retaining the integrity of the posterior ligament complex (PLC) as much as possible.

The purpose of this study is: (i) to observe dural and spinal cord injuries to evaluate the safety of the BLP laminectomy of vertebral lamina transection, (ii) and to compare these with the traditional laminectomy in terms of incision and bone window length, time to remove the vertebral lamina, postoperative epidural effusion volume, and vertebral lamina displacement 2 weeks and 3 months postoperatively to evaluate the superiority of the BLP laminectomy.

Methods

We performed a retrospective analysis of patients with intradural tumors in the thoracolumbar segment (T4–L5) who underwent traditional or BLP laminectomy in the Department of Neurosurgery, General Hospital of Tianjin Medical University between October 2019 and July 2022.

Inclusion criteria were as follows: (1) tumor location (intradural tumors within the thoracolumbar segment, T4–L5), and (2) laminoplasty was required after tumor resection. The exclusion criteria were the following: (1) previous operation at the same site, and (2) destroyed vertebral appendages which impeded laminoplasty.

According to laminectomy methods, patients were divided into traditional laminectomy and BLP laminectomy groups. Age, sex, and tumor size, location, and depth of the patients in both groups were compared. The study was approved by the Ethics Committee of Tianjin Medical University General Hospital (NO. IRB2023-WZ-007).

Details on the Surgical Procedure

The patient lies prone. After general anesthesia, the tumor location and boundary, assessed according to preoperative MRI and intraoperative X-ray fluoroscopy, are marked. The upper and lower boundaries of the incision usually exceed the tumor boundary by about 2–3 cm. After exposing the vertebral lamina, an ultrasonic osteotome is used to cut the vertebral lamina on both sides of the bone window. Subsequently, the spinous process and vertebral lamina are laterally cut about 1–1.5 cm from the distal end of the upper and lower tumor boundaries. If necessary, the position of the transverse incision is adjusted to avoid the lamina space as much as possible. After tumor resection, both sides of the vertebral plate are fixed with miniature titanium plates, and the severed sphenoid break ends are fixed with open sutures.

Differences between the BLP and Traditional Method

Incision design: In the traditional laminectomy, the two ends of the incision usually exceed the boundary of the vertebral plate to be resected by approximately 2–3 cm, whereas in the BLP method, the upper and lower boundaries of the incision are usually approximately 2–3 cm from the two ends of the tumor without considering the boundary of the vertebral plate to be resected.

Bone window design: The traditional laminectomy involves exposing the entire vertebral plate covering the tumor and removing it completely, or biting off the adjacent part of the spinous process or the vertebral plate to further expand the operation space (Figure 1A). With the BLP laminectomy, usually approximately 1 cm of the upper and lower borders of the tumor is chosen as the upper and lower borders of the bone window, the spinous process and lamina are transected laterally, and the lamina is removed together with the ligamentum flavum and interspinous ligament (Figure 1B).

Assessment Methods

The incision length, bone window length, laminectomy time, and epidural effusion volume were recorded in both groups. Using magnetic resonance imaging (MRI), we compared the preoperative and 3-month postoperative laminar displacements, i.e., the sum of the relative displacements of the upper and lower ends of the returned lamina measured in the sagittal view, and the sum of the relative displacements of the two sides of the bone suture of the returned lamina measured in axial view (Figure 2).

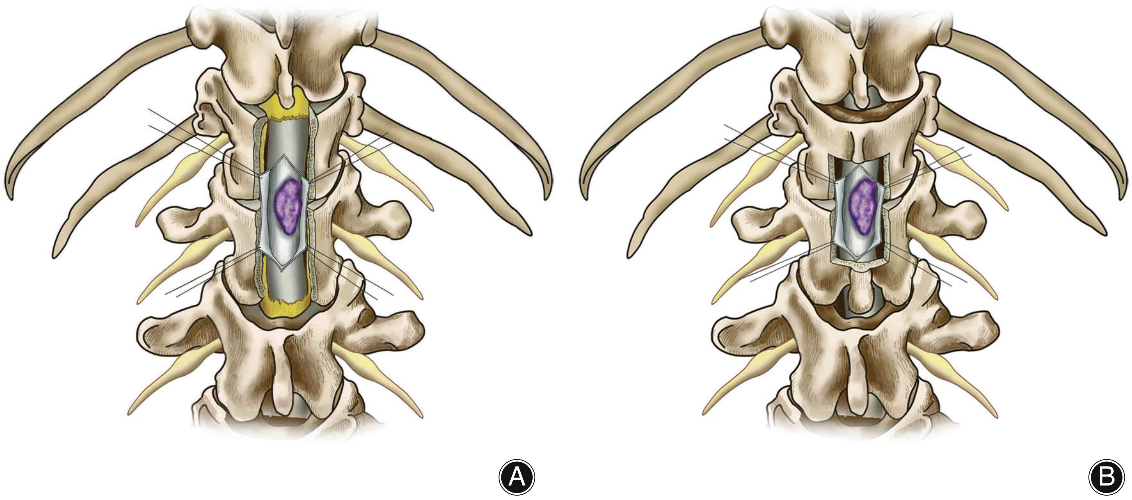

FIGURE 1 Illustration of the traditional and bone-to-bone ligament preserving (BLP) laminectomy. (A) Traditional laminoplasty: After cutting the interspinal ligament and the ligamentum flavum, all the lamina covering the tumor were removed completely. (B) BLP laminoplasty: Approximately 1 cm of the upper and lower boundary of the tumor is selected as the upper and lower boundary of the bone window, the spinous process and vertebral lamina are transversely cut, and the vertebral lamina together with the yellow ligament and interspinous ligament are taken out.

FIGURE 2 Main parameters of imaging measurements. The tumor length and depth, bone window length, and incision length were measured using sagittal MRI. The volume of epidural effusion was calculated by the Tada formula of the maximum diameter in sagittal and axial positions. The sagittal displacement of the vertebral lamina is the sum of the distance from the upper and lower ends of the vertebral lamina to the posterior edge of the vertebral body after the midline position measurement minus the sum of the distance from the same position before the operation. The axial displacement is the sum of the relative displacement of the returned vertebral lamina on both sides of the suture in the same axial image. MRI, magnetic resonance imaging.

Statistical Methods

The Wilcoxon rank sum test (z statistic) was performed on the indicators using SPSS software (version 26.0.0.0, IBM, Chicago, IL). Results were presented as mean ± standard deviation. $p < 0.05$ indicated significant differences.

Results

Baseline and Clinical Characteristics

A total of 86 patients with intradural tumors in the thoracolumbar segment were included according to the inclusion and exclusion criteria. The most common tumor pathologic types were neurilemmoma (39/86), meningioma (18/86), and ependymoma (9/86). The mean age of 51.4 years (16–74 years), and 31 participants were male and 55 were female. Of these, 39 had tumors located in the thoracic segments (T4–12) and 47 in the lumbar segments (L1–5), with a mean tumor length diameter of 29.7 mm in the sagittal position and a mean tumor depth (the distance of the tumor center from the skin) of 53.0 mm. Among them, 44 and 42 patients had the lamina removed using the traditional and BLP laminectomy, respectively. The average follow-up time was 12.6 ± 4.8 months. There were no significant differences in age, sex, and tumor size, location, or depth between the two groups (Table 1).

Surgical Time and Trauma

In terms of vertebral plate resection time between the two groups, the BLP laminectomy group required significantly lesser time than the traditional method group (5.786 ± 1.317 min vs. 8.477 ± 1.338 min, $p < 0.05$). In the sagittal position, the length difference between the incision/bone window and the tumor was 42.543 ± 7.556 mm and 19.400 ± 5.848 mm in the BLP laminectomy group, whereas the length difference between the incision/bone window and the tumor was 61.695 ± 10.680 mm and 33.332 ± 9.169 mm in the traditional laminectomy group. Both length differences were significantly smaller in the BLP compared to the traditional laminectomy group ($p < 0.05$) (Table 1).

Postoperative Lamina Displacement

MRI was reviewed at 2 weeks after surgery; by calculating the volume of sublaminar epidural fluid, we found that 1.883 ± 0.846 mL of fluid accumulated in the BLP and 2.414 ± 1.603 mL in the traditional laminectomy group. There was no significant difference in the volume of epidural fluid between the two groups ($p \geq 0.05$). Compared with the preoperative MRI, the total displacement of vertebral lamina was 1.964 ± 0.736 mm in the sagittal and 1.619 ± 0.764 mm in the axial position in the BLP laminectomy group, whereas in the traditional laminectomy group, the displacement was 2.114 ± 0.784 mm in the sagittal and 1.864 ± 0.795 mm in the axial position, albeit with no significant difference between the two groups ($p \geq 0.05$). In the BLP laminectomy group, the total displacement in the sagittal position was 2.067 ± 0.897 mm, and in the axial position, it was 1.702 ± 0.773 mm; meanwhile, in the traditional laminectomy group, it was 3.205 ± 1.133 mm in the sagittal position, and 1.909 ± 0.83 mm in the axial position. There was no significant difference in axial displacement between the two groups ($p \geq 0.05$); however, the sagittal displacement was significantly larger in the traditional laminectomy group ($P < 0.05$). In addition, the sagittal displacement increased significantly in the traditional laminectomy group at 3 months postoperatively ($P < 0.05$), while the axial displacement did not change significantly in the BLP laminectomy group ($p < 0.05$) compared to 2 weeks and 3 months postoperatively (Table 2).

Complications

All patients had no iatrogenic malformation during the follow-up period. Five patients with ependymoma and three patients with teratoma had significant neurological symptoms 1 week after surgery. However, these symptoms were significantly improved at the 3-month follow-up. In addition, one patient had cerebrospinal fluid leakage after surgery, which was cured after being sutured.

Discussion

Main Finding

Based on our findings, the BLP laminectomy does not increase the risk of spinal cord and dura mater injury, proving the safety of transverse laminectomy. Compared with the traditional laminectomy, the incision and bone window length of the BLP laminectomy group are smaller, indicating less traumatic surgical exposure. The laminectomy time in the BLP laminectomy group is shorter, suggesting that this method allows for easier lamina removal compared to the traditional laminectomy. In addition, compared with 2 weeks and 3 months postoperatively, the sagittal displacement of the BLP laminectomy group was smaller, indicating that the vertebral plate receipt was more stable. The detailed comparative analysis is reported below.

TABLE 1 Patients' characteristics

Parameters	Traditional laminectomy	BLP laminectomy	*Z* value	*p* value
Gender				
Male	20	11	1.849	0.064
Female	24	31		
Age	50.886 ± 14.088	51.905 ± 14.822	−0.259	0.795
Tumor size (mm)	30.714 ± 20.594	28.671 ± 21.164	0.406	0.684
Location				
T4-T12	20 (23.26%)	19 (22.09%)	0.020	0.984
L1-L5	24 (27.91%)	23 (26.74%)	0.097	0.923
Tumor depth (mm)	53.436 ± 9.909	52.514 ± 7.265	−0.039	0.969
Difference between incision and tumor length (mm)	61.695 ± 10.680	42.543 ± 7.556	7.119	<0.001*
Difference between bone window and tumor length (mm)	33.332 ± 9.169	19.400 ± 5.848	6.688	<0.001*
Time for removing vertebral lamina(min)	8.477 ± 1.338	5.786 ± 1.317	6.894	<0.001*
Epidural effusion volume 2 weeks after surgery (ml)	2.414 ± 1.603	1.883 ± 0.846	1.840	0.066

Abbreviation: BLP, Bone-to-bone Ligament Preserving.

TABLE 2 Comparative analysis of the vertebral lamina displacement (in mm)

Group	2 weeks	3 months	*Z* value	*p* value
BLP laminectomy				
Sagittal planes	1.964 ± 0.736	2.067 ± 0.897	0.355	0.722
Axial planes	1.619 ± 0.764	1.702 ± 0.773	0.585	0.559
Traditional laminectomy group				
Sagittal planes	2.114 ± 0.784	3.205 ± 1.133	4.718	<0.001*
Axial planes	1.864 ± 0.795	1.909 ± 0.83	0.245	0.807
	BLP laminectomy group	Traditional laminectomy group	*Z* value	*p* value
2 weeks				
Sagittal planes	1.964 ± 0.736	2.114 ± 0.784	0.880	0.379
Axial planes	1.619 ± 0.764	1.864 ± 0.795	1.645	0.100
3 months				
Sagittal planes	2.067 ± 0.897	3.205 ± 1.133	4.781	<0.001*
Axial planes	1.702 ± 0.773	1.909 ± 0.83	1.275	0.202

Abbreviation: BLP, Bone-to-bone Ligament Preserving.

Safety of Transverse Laminectomy Using Ultrasonic Bone Knife

The intradural epidural area was divided into the ligamentum flavum coverage area and the blank area.[4] We selected the ligamentum flavum coverage area to grind the vertebral lamina to avoid damaging the dura.[5] Unlike a rotary drill, which cuts bone, an ultrasonic osteotome oscillates at over 22,500 times per second with an offset range of 35–300 μm. Repeated impact crushes hard mineralized structures to achieve precise cuts, whereas softer adjacent tissues remain theoretically unaffected by ultrasonic oscillation.[6,7]

The sublaminar space is not covered by the ligamentum flavum, but the epidural space is relatively thick.[8] The epidural space in the thoracolumbar spine is serrated in the sagittal plane, with the narrowest part located on the cephalad side of the vertebral plate at a depth of 1.1–2.9 mm, the widest part located on the caudal side of the vertebral plate, and the interlaminar space at a depth of about 3.8–6.5 mm. The depth of the epidural space in the blank area is between the two.[9] The epidural space increased further in the prone position.[10] The epidural space consists of an epidural membrane and ligament.[11] The epidural space is filled with a semi-fluid fat structure.[12,13] In addition, the dura can withstand 3–6 mm of pushing with a 21-gauge puncture needle without being punctured despite being only 0.15–0.25 mm thick.[14] In addition to the protection of the epidural space and dura, the subdural space provides additional cushioning for the spinal cord.[15] Therefore, the operator will experience a significant drop when cutting the lamina with the ultrasonic bone knife; however, owing to the protection and cushioning of the epidural, dural, and subdural gaps, it is still safe to use the ultrasonic knife to cut the lamina laterally even in the blank area without ligamentum flavum coverage. In this study, 102 transverse laminae were cut, of which 46 were located in the subdural space, and none of them damaged the dura, spinal cord, or nerve roots.

The Extent of Laminectomy is more Flexible

To obtain sufficient space for subdural surgical manipulation, the ideal bone window range was approximately 1 cm from the upper and lower boundaries of the tumor. At least one side of the tumor border was located in the intervertebral space in 64 of the 86 patients with intradural tumors included in this study. The conventional approach usually involves complete resection of the tumor-covering vertebral plate, followed by resection of the adjacent portion of the spinous process and vertebral plate, or complete resection of the adjacent vertebral plate to obtain sufficient operative space. The BLP laminectomy is more flexible in the extent of resection of the lamina without removing all the lamina covering the tumor. We usually cut the lamina laterally in the area 1 cm from the upper and lower boundaries of the tumor and try to avoid the lamina space. If the ideal border of the bone window is in the interlaminar space and the ligamentum flavum is thicker, the outer part of the caudal lamina can be resected by adjusting its position appropriately, and the lamina can be easily removed together with the interlaminar ligamentum flavum. In this study, the differences in incision/window length and tumor length between the two methods were compared, and it was found that the incision length and the extent of the bone window were significantly smaller in the BLP laminectomy group than in the traditional laminectomy group, and the corresponding incision and muscle dissection required were also smaller.

Shorter Operating Time

In this study, by comparing the time to remove the lamina using an ultrasonic bone knife, we found that the time to remove the thoracolumbar lamina by the traditional laminectomy was 8.477 ± 1.338 min, while the time for the BLP laminectomy group was 5.786 ± 1.317 min, the time difference was significant ($p < 0.001$). It was significantly easier to remove the lamina using the BLP laminectomy. The spinous processes of the thoracic spine are long and have a greater angle of inclination, the width and height of the lamina gap are smaller, and the lateral aspect of the caudal lamina is covered by the cephalic lamina, causing problems in complete laminectomy. The T6 spinous process was the longest among the thoracic spinous processes with a mean length of 33.38 ± 2.94 mm, and the T7 tilt angle was the largest with a mean of 38.14 ± 2.48°. In addition, the width of the intervertebral space between T5 and T6 was the shortest, with an average of 9.63 ± 3.63 mm, and the height of the intervertebral space between T3 and T4 was the smallest, with an average of 5.20 ± 1.77 mm.[16] The coronal angle at the T12 level was 107 ± 9.6° in males and 106 ± 9.9° females, with the inferior articular eminence and medial lamina together forming the posterior wall of the spinal canal.[17] The upward extension of the lamina is obscured by the inferior edge of the lamina at the cephalic end, and the small space limits the visualization of the lamina occlusion forceps. It is usually necessary to remove part of the superior edge of the lamina or the medial articular process inferiorly after cutting the cephalic spinous process to obtain a sufficiently wide bone window. The BLP laminectomy requires no consideration of the spinal plate and cord, or the complete removal of the lamina and spinous process; it only necessitates determining the extent of removal of the upper and lower borders according to the bone window. An ultrasonic bone knife can remove the spinous process and the lamina vertically, and then pry at the upper and lower borders to loosen them, respectively.

With the increase in spinal stress, the length, width, and thickness of the ligamentum flavum from the cervical spine to the lumbar spine gradually increase, and the average thickness of the ligamentum flavum in the lumbar region is 4–6 mm, with a unilateral average width of 22.7 mm.[5,18] The wider ligamentum flavum tends to obscure the visualization of occlusal forceps and makes complete laminectomy difficult. The BLP laminectomy avoids cutting in the lamina interval where the ligamentum flavum is hypertrophic, even when cutting in the ligamentum flavum covered area of the lamina, which can be easily removed by prying at the superior and inferior bony sutures, because the ligamentum flavum's primary direction of travel is longitudinal.

More Stable Laminar Reimplantation

The cutting gap of an ultrasonic bone knife blade is usually 0.5–1.0 mm. A smaller cutting gap indicates less bone loss and less axial displacement, which facilitates better repositioning and fusion of the returned lamina. In addition, in this study, we found that the sagittal displacement of the returned lamina in the traditional laminectomy group increased at 3 months postoperatively, presumably because the relative extent of the resected lamina was larger and the contracture of the ligamentum flavum between the laminae and the postoperative spinal activity caused a pitching movement of the returned lamina. In the BLP laminectomy, the contact surface between the lamina and the window was three-sided because the bone suture at both ends of the window was U-shaped, whereas, in the traditional laminectomy, the contact between the lamina and window was two-sided.

In addition, the posterior ligament complex (PLC) serves as the primary stabilizer of the spine by forming a posterior tension band, the primary role of which is to limit spinal flexion, axial rotation, and distraction.[19] Medically induced destruction of the PLC is an important cause of postoperative deformity of the spine, and it is important to preserve the supraspinous and interspinous ligamentous structures. This BLP laminectomy approach attempts to sever the spinous process and lamina as much as possible, which can preserve the integrity of the PLC to the maximum extent. However, further long-term comparative observations are needed to determine which is more beneficial for long-term spinal stability: scar healing by severing the PLC or bone healing by severing the spinous process laminae.

Taken together, it is safe to use an ultrasonic bone knife to transect laminae. This BLP laminectomy requires a smaller bone window for the removal of thoracolumbar tumors, and the corresponding incisions and muscle stripping are smaller and relatively less invasive. The new technique also allows easier removal of laminae and takes less time overall. In addition, the three bony contact surfaces allow for less displacement of the re-implanted lamina, which facilitates better fusion of the lamina. This BLP method also improves the integrity of the PLC, which may facilitate the repair of spinal stability.

Strengths and Limitations of this Study

This is the first report on the use of a BLP technique for laminectomy in the resection of thoracolumbar tumors, and we realize many advantages brought by the improvement of this technique. It is expected that this new idea of laminectomy may have reference value for neurosurgeons. However, this study also has the following limitations. This was a retrospective study, which reduces the quality level of the study. In addition, this study did not include factors such as the pathological type of tumor and the surgeon proficiency, which may have a partial impact on the results. In addition, this study only analyzed the displacement of vertebral lamina within 3 months postoperatively and lacked follow-up data on mid- and long-term vertebral lamina displacement and bone healing.

Conclusion

This BLP laminectomy requires a smaller bone window for the removal of thoracolumbar tumors, and the corresponding incisions and muscle stripping are smaller and relatively less invasive. The BLP technique also allows easier removal of laminae and takes less time overall. In addition, the three bony contact surfaces allow for less displacement of the re-implanted lamina, which facilitates better fusion of the lamina. The BLP laminectomy also improves the integrity of the PLC, which may facilitate spinal stability reacquisition. Finally, our study has proved that the ultrasonic bone knife can be safely used for transverse cutting of the vertebral lamina even in the thoracic region without the coverage of the ligamentum flavum.

Author Contributions

Conceptualization: Tao Zhu and Hongtao Rong; Methodology: Hongtao Rong and Sipeng Li; Investigation: Yuhang Diao and Bowen Zheng; Formal Analysis: Sipeng Li and Ruiguang Zhang; Writing—Original Draft: Hongtao Rong and Sipeng Li; Writing—Review & Editing: Ruiguang Zhang and Bowen Zheng; Visualization and supervision: Tao Zhu; Funding Acquisition: Tao Zhu and Hongtao Rong. Hongtao Rong, Sipeng Li, and Ruiguang Zhang contributed equally to this work and share first authorship. All authors contributed to the article and approved the submitted version.

Acknowledgments

The authors would like to thank Professor Junping Wang's team for their support with postoperative imaging follow-up.

Funding Information

This work was supported by the Medical Health Science and Technology Project of Tianjin Municipal Health Commission (ZC20175), and the Scientific Research Program of Tianjin Municipal Science and Technology Bureau (NO. 19ZXDBSY00040).

Conflict Of Interest

The authors declare no conflict of interest in this study.

References

1. Jiang L, Luo J, Gong H, et al. Clinical and biomechanical study of laminoplasty for thoracic and lumbar intradural tumors. J Clin Med. 2023;12:355.
2. Önen MR, Naderi S. Bone-to-bone ligament preserving laminoplasty technique for reconstruction of laminae. J Craniovertebr Junction Spine. 2021;12:61–4.
3. Wiedemayer H, Sandalcioglu IE, Aalders M, Wiedemayer H, Floerke M, Stolke D. Reconstruction of the laminar roof with miniplates for a posterior approach in intraspinal surgery: technical considerations and critical evaluation of follow-up results. Spine. 2004;Phila Pa 1976(29):E333–42.
4. Ahmadi SA, Suzuki A, Terai H, Tamai K, Akhgar J, Hoshino M, et al. Anatomical analysis of the human ligamentum flavum in the thoracic spine: clinical implications for posterior thoracic spinal surgery. J Orthop Sci. 2019;24:62–7.
5. Akhgar J, Terai H, Rahmani MS, Tamai K, Suzuki A, Toyoda H, et al. Anatomical analysis of the relation between human ligamentum flavum and posterior spinal bony prominence. J Orthop Sci. 2017;22:260–5.
6. Hu X, Ohnmeiss DD, Lieberman IH. Use of an ultrasonic osteotome device in spine surgery: experience from the first 128 patients. Eur Spine J. 2013;22:2845–9.
7. Wu L, Wang S. Effect of ultrasonic osteotome on therapeutic efficacy and safety of spinal surgery: a system review and meta-analysis. Comput Math Methods Med. 2022;2022:9548142.
8. Newell RL. The spinal epidural space. Clin Anat. 1999;12:375–9.
9. Reynolds AF Jr, Roberts PA, Pollay M, Stratemeier PH. Quantitative anatomy of the thoracolumbar epidural space. Neurosurgery. 1985;17:905–7.
10. Mustafa K, Milliken RA, Bizzarri DV. The advantage of the prone position approach to the lumbar epidural space. Anesthesiology. 1983;58:464–6.
11. Santos J, Kalhorn SP. Anatomy of the posterolateral spinal epidural ligaments. Surg Neurol Int. 2021;12:33.
12. Hirabayashi Y, Saitoh K, Fukuda H, Igarashi T, Shimizu R, Seo N. Magnetic resonance imaging of the extradural space of the thoracic spine. Br J Anaesth. 1997;79:563–6.
13. Reina MA, Franco CD, López A, Dé Andrés JA, van Zundert A. Clinical implications of epidural fat in the spinal canal. A scanning electron microscopic study. Acta Anaesthesiol Belg. 2009;60:7–17.
14. Zarzur E. The posterior epidural space depth. Reg Anesth Pain Med. 1998;23:108–9.
15. Imbelloni LE, Quirici MB, Ferraz Filho JR, Cordeiro JA, Ganem EM. The anatomy of the thoracic spinal canal investigated with magnetic resonance imaging. Anesth Analg. 2010;110:1494–5.
16. Leng LN, Ma HJ, Si DW. A morphometric study of the thoracolumbar spine spinous process and lamina space in the Chinese. Folia Morphol. 2021;80:665–74.
17. Ebraheim NA, Xu R, Ahmad M, Yeasting RA. The quantitative anatomy of the thoracic facet and the posterior projection of its inferior facet. Spine (Phila Pa 1976). 1997;22:1811–7. discussion 1818.
18. Winkler PA, Zausinger S, Milz S, Buettner A, Wiesmann M, Tonn JC. Morphometric studies of the ligamentum flavum: a correlative microanatomical and MRI study of the lumbar spine. Zentralbl Neurochir. 2007;68:200–4.
19. Bizdikian AJ, El Rachkidi R. Posterior ligamentous complex injuries of the thoracolumbar spine: importance and surgical implications. Cureus. 2021;13:e18774.