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ORIGINAL RESEARCH

Ultrasonic Bone Scalpel in Anterior Cervical Discectomy and Fusion Enhances Outcomes and Foraminal Decompression in Cervical Radiculopathy: A Retrospective Cohort Study

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Study Design: Retrospective cohort study. Objective: This study compared the safety and efficacy of ultrasonic bone scalpel-assisted direct decompression versus conventional direct decompression (using high-speed drills and Kerrison rongeurs) in anterior cervical discectomy and fusion (ACDF) for cervical radiculopathy with foraminal bone stenosis. This retrospective cohort study included 94 patients who underwent cervical foraminal stenosis surgery from 2019 to 2022. Group A (n=48) received traditional direct decompression using a high-speed drill and Kerrison rongeur, while Group B (n=46) underwent direct decompression using a combination of drilling and ultrasonic bone scalpel. Clinical outcomes were assessed using Visual Analog Scale (VAS) for pain, Neck Disability Index (NDI) for functional disability, and smallest oblique sagittal area (SOSA) of the neural foramen on CT scans to evaluate foraminal enlargement.

Results: Patients in Group B demonstrated significantly greater improvements in VAS and NDI scores ($p<0.01$), with a larger mean SOSA (73.85 mm² vs 50.00 mm²) compared to Group A. Additionally, Group B showed a reduction in blood loss and shorter operative time. No significant differences in complication rates, including dural tears or nerve root injuries, were found between the two groups.

Conclusion: The ultrasonic bone scalpel-assisted decompression technique offers significant advantages over traditional methods in terms of surgical outcomes, including better pain relief, functional recovery, and foraminal enlargement, while maintaining comparable safety profiles.

Keywords: ultrasonic bone scalpel, anterior cervical discectomy and fusion, ACDF, foraminotomy, smallest oblique sagittal area

Introduction

Cervical radiculopathy due to foraminal stenosis, a degenerative spinal condition, arises from the multifactorial interplay of uncovertebral joint hypertrophy, uncinate process joint osteophyte formation, and intervertebral disc space collapse, ultimately leading to mechanical compression of the osseous neural foramen.[1,2] Although anterior cervical discectomy and fusion (ACDF) can effectively alleviate discogenic neural compression through intervertebral distraction, its inherent anatomical limitations[3] restrict its ability to improve osseous foraminal stenosis, failing to adequately address the osseous narrowing of the neural foramen caused by uncovertebral joint hyperplasia. In comparison to posterior or combined anterior-posterior approaches, the anterior approach provides more direct and less traumatic decompression of the uncinate process and posterolateral osteophytes. However, the complex vascular and neural anatomy surrounding the uncovertebral joint limits its application, and the complete enlargement of the neural foramen has long been constrained by challenges related to technical safety.

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The traditional direct decompression technique relies on the combined use of a high-speed drill and a Kerrison rongeur. Its technical limitations primarily arise from the physical characteristics of these instruments. The heat damage and torque effect generated by the high-speed rotating drill significantly increase the risk of dural tears and nerve root injuries. Additionally, the non-selective cutting of bone tissue necessitates excessive exposure of the vertebral artery when removing lateral uncinate osteophytes, which leads to a high incidence of vertebral artery injury with reported rates the anterior surgical approach ranging from 0.3–0.5%.[4–6] Current protective strategies including preoperative imaging assessment, intraoperative anatomical landmark guidance (eg, medial to uncinate process and longus colli), and real-time imaging monitoring have only partially mitigated these risks.[7,8] Furthermore, the accumulation of bone debris and bleeding during surgery often compels the surgeon to prematurely terminate the decompression, resulting in residual bony stenosis that may trigger persistent radicular symptoms postoperatively. These technical limitations highlight a critical contradiction in the field of spinal surgery: the pursuit of thorough decompression is frequently constrained by the safety thresholds of existing instruments.

The emergence of ultrasonic bone scalpel technology offers a novel approach to address this dilemma. This device converts electrical energy into longitudinal high-frequency mechanical vibrations through piezoelectric crystals, enabling selective bone cutting by leveraging the significant acoustic impedance difference between bone and soft tissues.[9] The evolution of ultrasonic osteotomy has demonstrated superior precision in minimizing neurovascular thermal and mechanical trauma compared to conventional high-speed drilling instrumentation.[10,11] Its unique "cold cutting" characteristic confines the thermal damage range to within a depth of 1 mm (temperature <50°C), while eliminating rotational shear forces, theoretically reducing the risk of neurovascular injury significantly.[12,13] A comprehensive analysis of early spinal surgery cases reveals that the cumulative incidence of dural tears with ultrasonic bone scalpel is 0.4%, which is significantly lower than the 2.91% associated with traditional high-speed drills combined with Kerrison rongeurs.[14] However, existing studies have mainly focused on posterior or thoracolumbar surgery, and the safety and efficacy of ultrasonic bone scalpel in the unique anatomical context of anterior cervical root canal bone stenosis requiring foraminotomy involving millimeter-scale surgical gaps still lack sufficient validation.

The integration of ultrasonic bone scalpel into the ACDF surgical procedure presents unique opportunities and challenges. Unlike the relatively accommodating anatomical environment of posterior decompression, anterior uncinate process resection necessitates the establishment of a precise operative plane between the medial aspect of the vertebral artery and the lateral aspect of the spinal cord. Traditional techniques depend on the surgeon's subjective judgment of tactile feedback from the drill, whereas the tissue-selective cutting characteristics of ultrasonic bone scalpel theoretically permit more precise osteophyte removal under visual conditions. However, whether this technical advantage translates into objective increases in foraminal volume or improvements in clinical outcomes remains unsupported by high-quality evidence. Notably, previous studies have either focused on indirect decompression effects[3] or evaluated the efficacy of ultrasonic bone scalpel in the absence of controlled designs.[15] There is still a lack of controlled studies comparing ultrasonic bone scalpel with traditional direct decompression techniques within the ACDF framework, which may prolong clinical equipoise in technology selection within this field.

Study Design and Data Sources

This retrospective cohort study compared the outcomes of patients with bony cervical stenosis who underwent either traditional foraminotomy or a novel technique involving drilling and ultrasound bone scalpel decompression between 2019 and 2022. As an evaluation of previously performed surgical interventions, no randomization was conducted for treatment allocation. The study utilized existing patient data from the hospital, forming two cohorts based on the surgery date and the recorded technique. All data were extracted from the hospital's electronic medical record system. Institutional review board and ethics committee approval (approval number: BYL20220536) was obtained prior to initiating data retrieval and analysis. Patient consent was waived by the ethics committee due to the retrospective nature of the study, with all patient data handled confidentially. This study was conducted in accordance with the principles of the Declaration of Helsinki[16] of the World Medical Association and all procedures involving human participants were performed in compliance with relevant ethical standards.

Sample Size Estimation

To ensure adequate statistical power for detecting significant differences between the traditional decompression group (Group A) and the ultrasonic bone scalpel-assisted group (Group B), an a priori sample size calculation was conducted. Based on preliminary data and previous studies, which suggest a relatively large effect size (Cohen's d = 0.8) for improvements in Visual Analogue Scale (VAS), Neck Disability Index (NDI) scores and minimum oblique sagittal area (MOSA), we aimed to achieve 95% statistical power at a significance level of $\alpha = 0.05$. Utilizing G*Power software (version 3.1),[17] the required sample size was determined to be a total of 84 participants, with 42 patients allocated to each group.

Participants

Participants included in this study underwent cervical foraminal stenosis surgery performed by the senior author from January 2019 to December 2022. The inclusion criteria were as follows: (1) patients aged under 80 years; (2) radiologically confirmed bony foraminal stenosis (with the smallest oblique sagittal area (SOSA) of the neural foramen <25.95 mm²) based on established morphometric criteria;[18,19] (3) patients who had failed non-surgical treatment for at least six weeks prior to surgery; (4) patients presenting with typical radicular symptoms and imaging findings consistent with the segmental localization of symptoms and signs; (5) patients with lesions involving fewer than three segments.

The exclusion criteria were as follows: (1) patients whose cervical foraminal stenosis resulted from soft tissue factors such as disc protrusion or ligamentous hypertrophy, rather than osteophyte formation; (2) patients diagnosed with cervical instability; (3) patients with a history of cervical spine surgery; (4) patients with any history of neurological disorders; (5) cases suspected of infection or malignancy; and (6) patients exhibiting abnormal spinal cord signals on cervical magnetic resonance imaging.

The cases were divided into two groups based on the innovation timeline of surgical instruments: Group A (Traditional Technique Group) comprised cases from 2019 to 2020 (n=48), in which a high-speed drill was utilized to create a bone window. This was followed by the application of Kerrison rongeurs to remove the uncinate process and osteophytes, thereby completing the foraminotomy. Group B (ultrasonic bone scalpel Technique Group) included cases from 2021 to 2022 (n=46), where, following the preliminary operation with the drill, an ultrasonic bone scalpel was employed to excise the uncinate process and osteophytes, also completing the foraminotomy.

Interventions

General anesthesia with endotracheal intubation was administered for this procedure. The patient was positioned supine with the neck extended. A cervical anterior approach was utilized, which involved sequential incisions through the skin and subcutaneous tissue, followed by dissection of the sternocleidomastoid muscle and deep fascia to progressively expose the anterior vertebral body. Accurate positioning was confirmed using a localization needle under C-arm fluoroscopic guidance. A parallel retractor was then inserted up to the posterior margin of the vertebral body. With one hand maintaining distraction of the intervertebral space, a Caspar retractor (Caspar® Radiolucent Cervical Retractor System, Aesculap AG, Tuttlingen, Germany) was secured to maintain intervertebral separation. Under direct visualization, the anterior longitudinal ligament was carefully excised, followed by an incision into the annulus fibrosus of the intervertebral disc.

The disc material was meticulously extracted using nucleus forceps and curettes until the posterior edge of the vertebral body was reached. Subsequently, an operating microscope (Leica M525 OH4 surgical microscope, Leica Microsystems, Wetzlar, Germany) was positioned to facilitate further procedures. Under microscopic guidance, any remaining disc material and cartilaginous tissue were thoroughly removed, thereby directly decompressing the anterior nerve root. The focus then shifted to the decompression of the posterolateral root canal space containing the nerve roots, which traverse through bony foramina below the small uncinate process joints lateral to the spinal cord, all under continuous microscopic visualization.

For the 2021–2022 cohort of combined drilling and ultrasonic bone scalpel group, initial attention was focused on using a drill to grind bone spurs and gradually remove prominent hook processes. The removal is stopped when cancellous bone bleeding occurs. Then, the focus shifts laterally, using a square-headed spatula (Figure 1) ultrasonic

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bone scalpel (BoneScalpel, Misonix, Inc., Farmingdale, NY, USA) to create a small opening along the outer wall of the hook process. The ultrasonic bone scalpel was introduced into the foraminotomy and the hypertrophic bone overgrowth was carefully removed posteriorly and laterally. The posterior longitudinal ligament was then incised and the patency of the intervertebral foramen was verified using a nerve hook, and the osteophyte and uncinate process could be further removed using the ultrasonic bone scalpel if needed. When the nerve hook can easily and unobstructed access to the anterior foramen and the nerve root outlet, sufficient decompression is confirmed to complete the foraminotomy[20] (as is shown in Figure 2 and Video S1). Prior to placement of cervical interbody fusion devices, the intervertebral space is moderately expanded using a distractor device. A standard surgical incision includes the insertion of a drainage tube.

Evaluation Indicators

Measurement of the Minimum Oblique Sagittal Area of the Cervical Intervertebral Foramen

In this study, we adhered to the methodologies established by previous research[18] to reconstruct the neural foramen using Mimics software (Version 20.0, Materialise, Belgium). We evaluated the efficacy of surgical decompression based on the SOSA of the neural foramen (as is shown in Supplementary Figures 1–3) Our research team initially introduced the concept of MOSA in earlier studies, proposing that it not only offers substantial reference value for diagnosing bony stenosis of the cervical neural foramen but also aids in identifying patients suitable for foraminal decompression surgery, thereby serving as a critical criterion for surgical indications.[18,19]

Safety and Efficacy Evaluation Indicators

The key outcomes of the evaluation are related to the safety and effectiveness of each surgical technique. Safety endpoints include rates of cerebrospinal fluid leakage, nerve injury (motor weakness), postoperative hematoma requiring reoperation, and other complications. The efficacy assessment is done using patient-reported VAS pain scores for the neck and arm, ranging from 0–10 (0=no pain, 10=worst pain).[21] These scores are obtained during preoperative clinic visits and then at standard postoperative intervals of 1 week, 6 weeks, 3 months, 6 months, and 1 year. Functional disability is also evaluated using the NDI questionnaire on a scale of 0–100 (higher score = worse disability). This questionnaire is administered during preoperative visits as well as all postoperative follow-up visits in the electronic medical record template.[22] The calculation formula for NDI improvement percentage is: ((preoperative NDI score - postoperative NDI score) / preoperative NDI score) × 100%.

Figure 1 The square-headed spatula-shaped ultrasonic bone scalpel used in the present surgery.

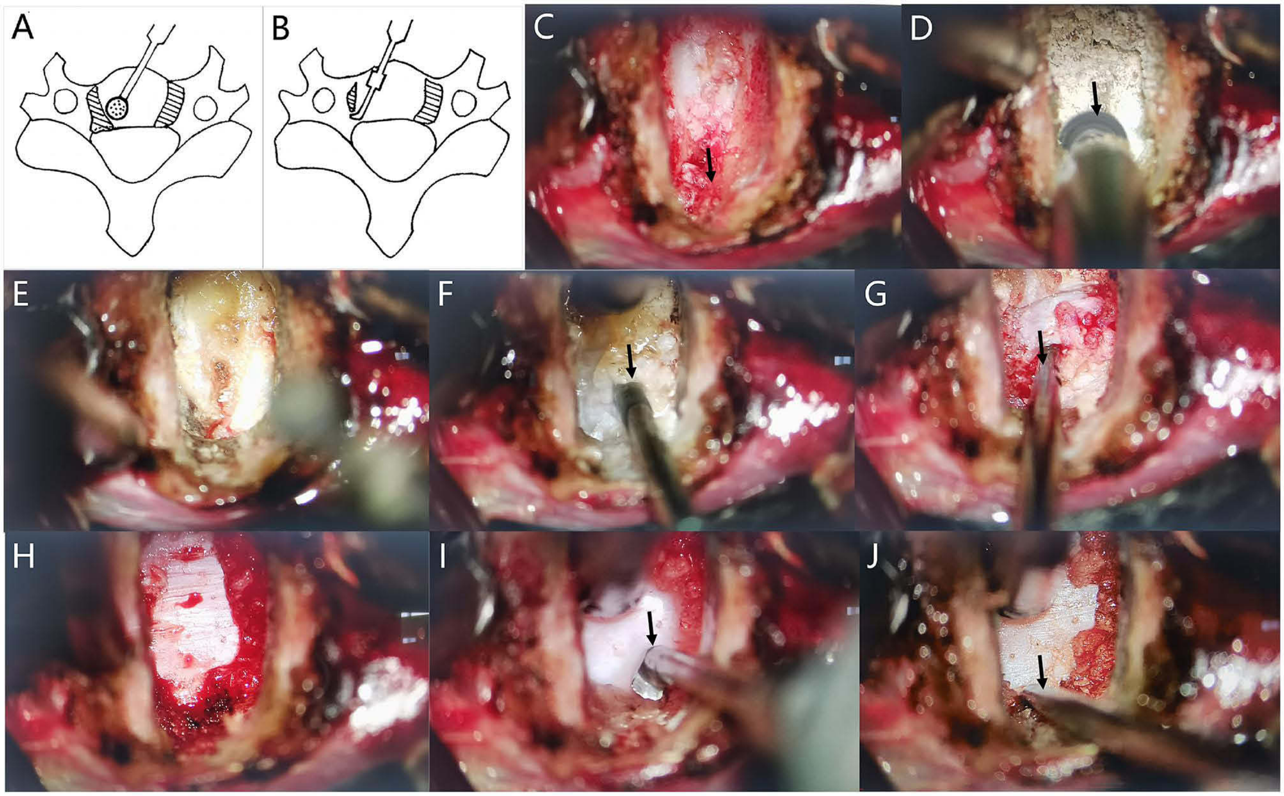

Figure 2 Schematic diagram (**A** and **B**) and intraoperative photograph (**C**–**J**) of the application of ultrasonic osteotome in foraminotomy. Cranial direction is to the left. (**C**) After complete resection of the disc, the margin of the uncinate joint (small black arrow) is exposed, (**A**–**D**) the inner wall of the uncinate process is trimmed with a diamond bit (small black arrow) to thin the bone into a thin shell, (**E**) removal is stopped when cancellous bone hemorrhage occurs. (**B**–**F**) Osteotomy was performed at the posterior edge of the uncinate process with square-headed spatula-shaped ultrasonic bone scalpel as shown in Figure 1, which was inserted into the intervertebral foramen to further remove hyperplastic osteophytes behind the uncinate process, (**G**) posterior longitudinal ligament was resected using nerve hooks (small black arrow), (**H**) dura mater was exposed, (**I**) bone hyperplasia was further resected with ultrasonic bone scalpel, and (**J**) nerve hook (small black arrow) was subsequently used to verify the patency of the intervertebral foramen, and foraminotomy was completed when the nerve hook could easily and unobstructed access to the anterior foramen and to the nerve root outlet.

Data Collection and Statistical Analysis

Data pertaining to patient demographics, clinical characteristics, surgical details, and outcome measures were systematically collected from the hospital's electronic medical records. Continuous variables, such as age, Visual Analog Scale (VAS) scores, and Neck Disability Index (NDI) scores, were presented as means ± standard deviations. Categorical variables, including gender, smoking status, comorbidities, involved cervical segments, surgical laterality, and unilateral versus bilateral involvement, were summarized as frequencies and percentages. If bilateral lesions occur, the mean value of bilateral indicators should be incorporated into the scope of the study. Prior to conducting further statistical analyses, the distribution of all continuous variables was assessed using the Shapiro–Wilk test to evaluate normality. In cases where data exhibited a normal distribution ($P > 0.05$), an independent-samples *t*-test was utilized to examine differences between the two groups. For categorical variables, comparisons were conducted using either the chi-square test (χ^2) or Fisher's exact test, as appropriate. When data deviated from normality ($P < 0.05$), non-parametric tests, such as the Mann–Whitney *U*-test, were employed. Repeated-measures analysis of variance (ANOVA) was performed for continuous variables measured at multiple time points, followed by post-hoc tests if significant differences were detected. All statistical analyses were conducted using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). A two-tailed P-value of less than 0.05 was considered statistically significant.

Results

After applying all eligibility criteria, the final study cohort comprised 48 patients in Group A who underwent standard surgical decompression procedures between 2019 and 2022, and 46 patients in Group B who were treated with a novel combination of drilling and ultrasonic bone scalpel techniques.

Cohort Characteristics

As illustrated in Table 1, the baseline characteristics of the two groups were generally well-balanced, with no statistically significant differences observed. The mean age of patients in Group A was 55.4 ± 9.8 years compared to 57.2 ± 11.2 years in Group B (P = 0.4), indicating no significant difference between the groups. The proportion of males was also comparable, with 58% in Group A and 65% in Group B (P = 0.49). Similarly, the prevalence of current smokers did not differ significantly between the groups (Group A: 14.6%, Group B: 13.0%, P = 0.83). With respect to common comorbidities, there were no statistically significant differences in the incidence of diabetes (Group A: 15%, Group B: 17%, P = 0.71), hypertension (Group A: 25%, Group B: 30%, P = 0.56), or cardiovascular disease (Group A: 10%, Group B: 12%, P = 0.69). The distribution of affected cervical segments (C4/5, C5/6, C6/7, C4/5 and C5/6, C5/6 and C6/7) was evenly distributed between the groups, with no statistically significant differences observed (all P > 0.05). Similarly, there were no significant differences in the surgical side (right side: Group A: 92%, Group B: 93%, P > 0.05) or the extent of the lesion (Group A: 67% unilateral, Group B: 65% unilateral, P = 0.88). Preoperative clinical scores for

Table 1 Comparison of Baseline Information Between the Two Groups of Patients

Indicator	Group A (n=48)	Group B (n=46)	Statistics	P value
Age (years, (X±SD)	55.4 ± 9.8	57.2 ± 11.2	t = −0.83	0.4
Gender (male)	28 (58%)	30 (65%)	χ^2 = 0.47	0.49
Smoking (current smokers)	7 (14.6%)	6(13.0%)	χ^2 = 0.05	0.83
Diabetes (Yes)	7 (15%)	8 (17%)	χ^2 = 0.14	0.71
Hypertension (Yes)	12 (25%)	14 (30%)	χ^2 = 0.35	0.56
Cardiovascular Disease (Yes)	5 (10%)	6 (13%)	χ^2 = 0.16	0.69
Involved Segment			χ^2 = 1.03	0.90
C4/5	9 (19%)	8 (17%)		
C5/6	14 (29%)	15 (33%)		
C6/7	11 (23%)	10 (22%)		
C4/5 and C5/6	9 (19%)	6 (13%)		
C5/6 and C6/7	5 (10%)	7 (15%)		
Right-sided Surgery	44 (92%)	43 (93%)	χ^2 = 0.003	0.95
Unilateral/Bilateral (Unilateral)	32 (67%)	30 (65%)	χ^2 = 0.02	0.88
Preoperative (X±SD)				
VAS Score: Arm	6.8 ± 1.4	7.1 ± 1.7	t = −0.94	0.35
VAS Score: Neck	5.9 ± 1.6	6.2 ± 1.8	t = −0.85	0.39
NDI Score (X±SD)	58.2 ± 10.3	61.3 ± 9.8	t = −1.49	0.13

Notes: Group A: patients who underwent foraminotomy using conventional tools; Group B: patients who underwent foraminotomy by ultrasonic bone scalpel.
Abbreviations: SD, standard deviation; VAS, Visual Analogue Scale; NDI, Neck Disability Index.

Table 2 Comparison of Operation Time, Intraoperative Blood Loss (X±SD) and Completion Rate of Surgery

Indicator	A Group	B Group	Statistics	P value
Operation Time (min)	102±18	88±16	t=3.98	<0.01
Intraoperative Blood Loss (mL)	35±7	22±8	t=8.39	<0.01
Completion Rate of Surgery (%)	100	100	NA	NA

Notes: Group A: patients who underwent foraminotomy using conventional tools; Group B: patients who underwent foraminotomy by ultrasonic bone scalpel.
Abbreviations: SD, standard deviation; NA, Not Applicable.

upper limb pain (VAS: Group A: 6.8 ± 1.4, Group B: 7.1 ± 1.7), neck pain (VAS: Group A: 5.9 ± 1.6, Group B: 6.2 ± 1.8), and NDI scores (Group A: 58.2 ± 10.3, Group B: 61.3 ± 9.8) were comparable between the two groups, with no statistically significant differences noted (all P > 0.05). Overall, the baseline characteristics were well-balanced between the two groups.

Perioperative Results

As illustrated in Table 2, none of the patients experienced vertebral artery injury or other intraoperative complications, and no surgeries were abandoned or modified. The mean operative duration for Group A (traditional technique) was 102 minutes, while for Group B (ultrasonic bone scalpel technique), it was 88 minutes (p<0.01). Compared with an estimated blood loss of 35 milliliters in Group A, Group B exhibited a significantly lower estimated blood loss of 20 milliliters (p=0.02).

Clinical and Imaging Findings

Figure 3A, B and Supplementary Table 1 illustrate the improvement in radicular pain during postoperative follow-up assessments. Both groups exhibited a reduction in mean VAS arm pain scores within the first week of follow-up. However, patients in Group B, who underwent surgery using the ultrasonic bone scalpel, demonstrated a more significant

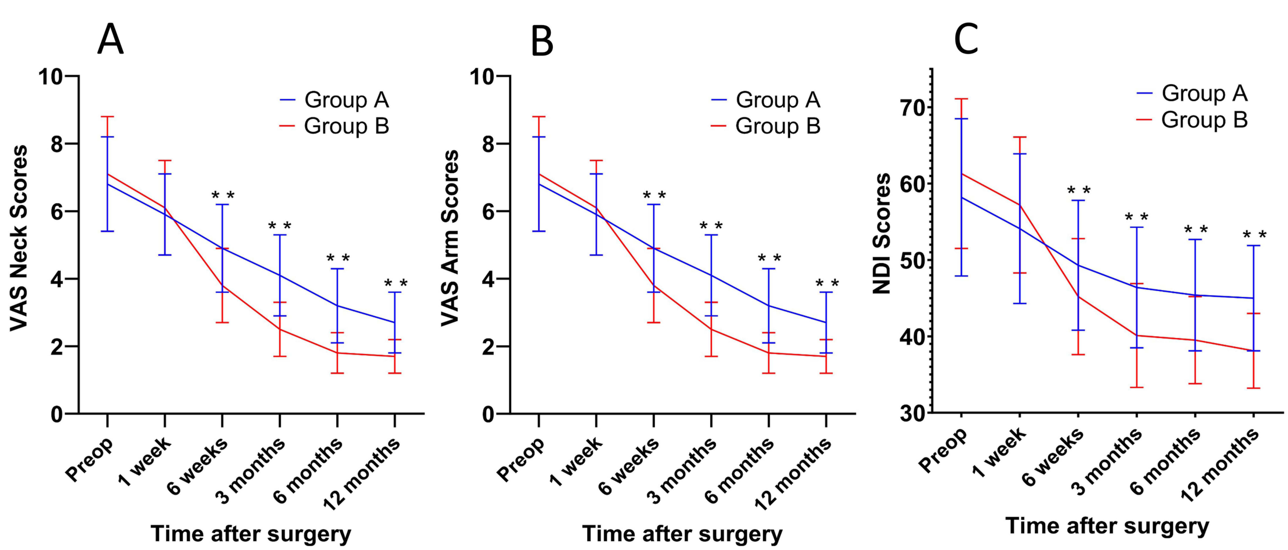

Figure 3 (**A**) The mean trend chart of preoperative and postoperative neck VAS; (**B**) The mean trend chart of preoperative and postoperative arm VAS; (**C**) The mean trend chart and that of preoperative and postoperative NDI; Group A patients who underwent foraminotomy using conventional tools; Group B patients who underwent foraminal decompression by ultrasonic bone scalpel. *means P value<0.05; **means P<0.01.
Abbreviations: VAS, Visual Analogue Scale; NDI, Neck Disability Index.

decrease in pain scores over the six-week period, eventually stabilizing with an average score below 2 (out of 10). In contrast, Group A, which utilized the traditional surgical technique, showed a gradual decline in pain scores but did not achieve an average score below 3 even after one year. The overall postoperative pain trajectory, as analyzed by repeated measures ANOVA, significantly favored the ultrasonic bone scalpel approach ($p<0.01$). Similar improvements were observed in neck pain scores.

The functional benefits derived from NDI ratings align with the trends observed in VAS results. As illustrated in Figure 3C and Supplementary Table 2, the baseline disability index scores were 58.2 and 61.3, respectively. At the six-month follow-up, patients who underwent conventional surgery demonstrated an average improvement of 8.9 points (representing a 15% improvement), whereas those treated with the ultrasonic bone scalpel showed an improvement of 16.1 points (a 26% improvement). Over the one-year follow-up period, the cohort utilizing the combined approach maintained a significant advantage in overall disability reduction, achieving an average improvement score of over 23 points (with a maximum improvement of 37.8%), compared to traditional techniques, which had a maximum improvement score of 13.2 points (23%). This may indicate enhanced long-term comfort and functionality resulting from bone resection procedures that preserve tissue integrity.

Preoperative CT evaluation revealed comparable degrees of nerve root compression in the neural foramen between the two groups. Postoperative CT scans demonstrated effective decompression of neural elements regardless of the surgical technique utilized. However, as quantified in Table 3, the use of an ultrasonic bone scalpel system resulted in a significantly larger SOSA of the Neural Foramen (mean 73.85 ± 9.96 mm² versus 50.00 ± 8.48 mm²) per level. The most significant difference was observed at the C5/6 level, where the minimum oblique sagittal area measured 32.93 ± 10.37 mm² after conventional techniques and 58.99 ± 11.61 mm² following surgery assisted by the ultrasonic bone scalpel system. These findings indicate that the ultrasonic bone scalpel facilitates more extensive foraminal enlargement, as illustrated in Figure 4.

Safety Results

In the control decompression group, 2 patients (4.2%) had a dural tear, while none of the patients in the ultrasonic bone cutter group had a dural tear ($p=0.49$). This risk reduction suggests the potential advantage of ultrasonic technology in dural protection, although it did not reach statistical significance in this smaller sample. Neither technique resulted in complications such as nerve root injury, spinal cord injury, wound infection, vertebral artery injury, or esophageal injury. One patient in the ultrasonic bone scalpel group experienced mild and transient hoarseness of voice, which resolved one-month post-surgery. No cases of recurrent laryngeal nerve paralysis were observed. Additionally, there were no reports of neurological deficits or deterioration, graft loosening, or failure of internal fixation.

Table 3 Comparison of the Smallest Oblique Sagittal Area of the Neural Foramen Between Two Groups of Patient (X±SD, mm^2)

Segment	A Group				B Group				t-value	P-value
	N	Pre	Post	Increment	N	Pre	Post	Increment		
C4/5	18	16.75±6.53	50.87±8.23	34.12±10.51	14	17.05±6.49	72.13±10.05	55.08±11.96	−5.27	<0.01
C5/6	28	15.69±6.33	48.62±8.21	32.93±10.37	28	15.87±5.98	74.86±9.96	58.99±11.61	−8.86	<0.01
C6/7	16	15.28±6.13	51.42±8.54	36.14±10.51	17	16.02±6.27	73.62±9.81	57.60±11.64	−5.55	<0.01
Average	62	15.90 ± 6.35	50.00 ± 8.48	34.10 ± 10.54	59	16.19 ± 6.14	73.85 ± 9.96	57.66 ± 11.77	−11.61	<0.01

Notes: Group A: patients who underwent foraminotomy using conventional tools; Group B: patients who underwent foraminotomy by ultrasonic bone scalpel. The Increment represents the difference in nerve root canal area before and after surgery. P<0.01 indicates a statistically significant difference in postoperative increments between the two groups.

Abbreviations: SD, standard deviation; Pre, Preoperative; Post, Postoperative.

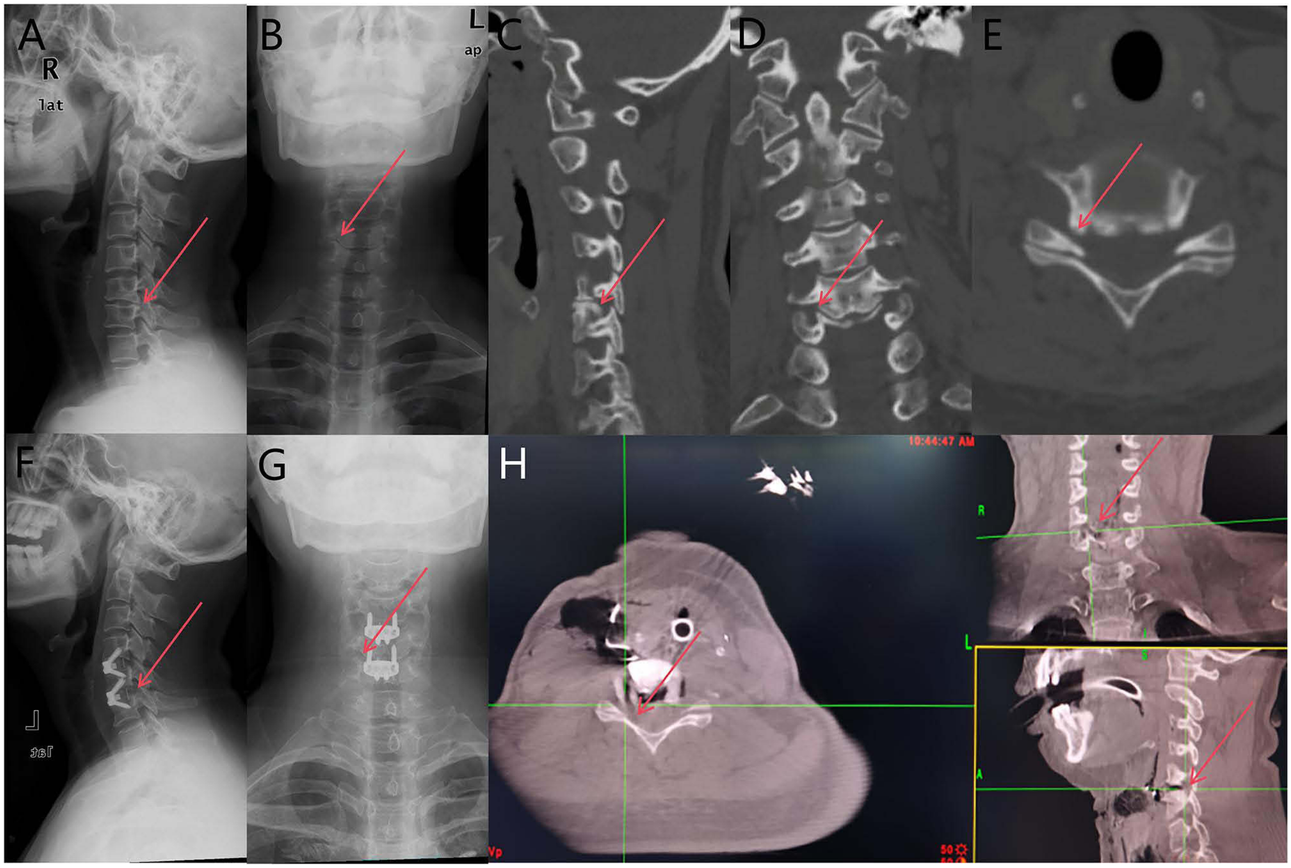

Figure 4 A case of cervical 5/6 bony foraminal stenosis was observed. Preoperative X-rays and CT scans (**A**–**E**) revealed stenosis of the right intervertebral foramen at the C5/6 level, which was caused by hypertrophy of the uncinate process. Postoperative X-rays and CT scans (**F**–**H**) demonstrated incomplete removal of the right uncinate process, complete elimination of hypertrophic osteophytes, and a noticeable enlargement of the right neural foramen.

Discussion

In this retrospective cohort study involving 94 patients who underwent multi-segmental nerve root decompression surgery for cervical spondylotic radiculopathy, the combined approach utilizing drilling and an ultrasonic bone scalpel exhibited significant improvements in pain relief, functional recovery, and surgical safety compared to conventional root canal decompression techniques. Postoperative CT scans quantitatively demonstrated enlargement of the neural foraminal space and an increase in the SOSA of the neural foramen, particularly in segments susceptible to osteophyte compression, such as C5/6. Notably, patients who underwent the tissue-preserving osteotomy experienced approximately 1-point reduction in neck and arm VAS scores within the first postoperative year compared to those who received conventional decompression. Additionally, there was a significant improvement of 13% to 14% in disability rating scale scores during follow-up assessments. Moreover, the novel approach markedly decreased the incidence of incidental dural injury. These findings indicate that incorporating this dual-modality paradigm may offer substantial benefits during the recovery phase.

In this study, we conducted foraminotomy via complete diskectomy following traditional ACDF surgery to enhance the visualization of the uncinate process within the disc space. Initially, we employed a high-speed drill under microscopic guidance to thin the medial wall of the uncinate process, thereby exposing the lateral wall in preparation for its resection. Simultaneously, the central bony protrusion was excised to establish the necessary operating space. Decompression was then initiated by introducing a square-headed spoon-shaped ultrasonic bone scalpel through the posterior uncinate process of the uncinate process. Compared to the methods proposed by Jho, Pakzaban, and Lee,[4,5,15] which focused on various aspects of decompression, this procedure prioritized the initial decompression of the medial wall and precisely controlled the lateral decompression range through visual guidance during drilling to achieve more comprehensive decompression. Subsequently, an ultrasonic bone curette was utilized to decompress the posterolateral

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aspect of the uncovertebral joint, leveraging ultrasound technology to manage irregular bone surfaces while protecting nerves and vessels. Partial preservation of the anterolateral uncinate process was performed to maintain stability and protect the anterolateral vertebral artery.

Despite the vertebral artery being only a few millimeters away from the uncinate process, it is typically located within the anterior two-thirds of the disc space, and osteophyte formation on the uncovertebral joint provides additional safety margin for ultrasonic bone scalpel operation. We implemented an incremental decompression approach, gradually removing bone until the nerve hook could easily and unobstructed access to the anterior foramen and to the nerve root outlet—our definitive endpoint for adequate decompression. This technique balances maximum neural decompression with vertebral artery protection. However, this approach necessitates careful preoperative radiological examination to determine vertebral artery course, osteophyte morphology, and potential anatomical variations. By combining meticulous preoperative planning with this incremental decompression technique, we achieved comprehensive foraminal decompression while maintaining safe distance from neurovascular structures throughout the procedure. Finally, interbody fusion was conducted to address instability caused by uncinate process resection and discectomy. The use of an ultrasonic bone scalpel enhanced decompression efficiency due to its tissue selectivity and cavitation effect, thereby reducing operative time and intraoperative bleeding.

The ultrasonic bone scalpel group demonstrated superior pain relief and functional improvement compared to the control group. This can be attributed to several key factors: the small amplitude maintained during cutting, the self-flushing cooling system, the absence of rolling movement, and the generation of smaller bone debris particles.[23–25] These characteristics collectively minimize thermal damage and mechanical stimulation to the nerve root, which likely explains the lower incidence of dural tears in the ultrasonic bone scalpel group. Additionally, the minimal reaction force on the handle and the stable nature of the procedure reduce the risk of soft tissue entrapment or tearing, thereby decreasing the likelihood of dura mater or spinal cord injury.[24,26] Notably, neither group experienced any instances of vertebral artery or nerve root injuries, indicating that these complications can be effectively mitigated through the application of appropriate surgical techniques and microscopic approaches. Imaging analysis provided objective evidence supporting the favorable clinical outcomes observed with combined osteotomy. Specifically, postoperative CT scans demonstrated a significantly larger foramen size following the use of the ultrasonic bone scalpel, which is critical for achieving adequate nerve root decompression. The SOSA of the neural foramen, a validated diagnostic parameter for cervical radiculopathy previously established by our team,[18,19] averaged 73.85 mm² per segment after osteotomy compared to 50.00 mm² after conventional decompression. This suggests that more comprehensive decompression of the foraminal space may result in reduced residual nerve root impingement and irritation, potentially contributing to the superior clinical outcomes observed in the ultrasonic bone scalpel group.

Several key aspects of our study design and population should be considered when interpreting the results. This study utilized a retrospective design, which may introduce selection bias and challenges related to incomplete data, thereby limiting the ability to establish causality. To ensure a balanced cohort that accurately reflects similar disease progression, we included only patients with moderate to severe foraminal stenosis confirmed by objective evidence and who had failed conservative treatment. In cases involving milder radiculopathy or where soft disc herniation is the primary compressive lesion, the benefits of combined osteotomy may be less evident. Future research should systematically investigate the efficacy and safety of this combined technique across a wider range of cervical radiculopathy presentations. Furthermore, choosing patients with less than three affected segments might make it challenging to extend the research findings to more complex or multi-layered cases. Although surgeries were conducted by an experienced spine surgeon to maintain procedural consistency, this may limit the generalizability of our findings to other clinical settings. The learning curve associated with integrating ultrasound techniques into surgical practice necessitates further exploration, underscoring the importance of comprehensive training and guidance for surgeons. Establishing standardized protocols for patient selection, surgical procedures, and postoperative care would enhance the integration of this approach into routine clinical practice. Moreover, the absence of long-term imaging data on fusion rates and adjacent segment disease in our study represents a significant limitation. Future studies with extended follow-up periods and serial radiographic evaluations beyond one year are essential to comprehensively assess the long-term impact of the ultrasonic bone scalpel on cervical spine health.

In conclusion, ultrasonic bone scalpel-assisted decompression provides better pain relief, functional recovery, and foraminal decompression compared to traditional methods, with reduced blood loss and shorter operative time. Both techniques have similar safety profiles, supporting the use of ultrasonic bone scalpel in cervical decompression surgeries. Further studies are needed to confirm long-term benefits.

Data Sharing Statement

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Ethical Approval Statement

This study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Shenzhen Baoan District People's Hospital (approval number: BYL20220536). Informed consent was waived due to the retrospective design of the research, which involved anonymized analysis of existing clinical data.

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Disclosure

The authors declare no conflicts of interest in this work.

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