Changes in Foraminal Geometry with Anterior Decompression versus Keyhole Foraminotomy in the Cervical Spine: A Biomechanical Investigation

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Background Context: Anterior cervical discectomy and fusion (ACDF) with or without uncovertebral joint resection (UVR) and posterior keyhole foraminotomy (F) are established operative procedures to treat cervical disc degeneration and radiculopathy. Studies have demonstrated reliable results with each procedure, but none have compared change in neuroforaminal area between indirect and direct decompression techniques.

Purpose: The purpose of this study is to determine which cervical decompression method most consistently increases neuroforaminal area and how that area is affected by neck position.

Study Design/Setting: Six human cervical functional spinal units (C5-6 and C6-7) underwent sequential decompression.

Methods: Each level received the following surgical treatment: bilateral foraminotomy (F), ACDF, ACDF+uncovertebral resection (UVR), and F+ACDF. Multidirectional pure moment flexibility testing combined with 3D C-arm imaging was performed after each procedure (Fig. 1) to measure minimum cross-sectional area of each foramen in three different neck positions: neutral, flexion, and extension.

Results: Neuroforaminal area increased significantly with F versus intact in all positions (Fig. 2). ACDF did not produce significant differences in area versus intact in any position. A significant decrease in area was observed for ACDF in extension (40 mm^2) versus neutral (55 mm^2). F+ACDF did not significantly increase area compared to F in any position. UVR did not produce any statistically significant changes in area across positions.

Conclusion: All procedures increased neuroforaminal area. F and F+ACDF produced the greatest increase in area and also maintained the area in extension more than anterior-only procedures. UVR did not significantly alter the area compared to ACDF alone. With a stable cervical spine, F may be preferable to directly decompress the neuroforamen; however, ACDF continues to have an important role for indirect decompression and decompression of more centrally located herniated discs. Our findings pertain mostly to bony stenosis of the neuroforamen and may not apply to soft disc herniation.

Degenerative disc disease in the cervical spine can cause neck pain, myelopathy and/or radiculopathy. Radiculopathy or nerve root compression can be caused by uncinate osteophytes, facet cyst, facet hypertrophy or disc herniation. To use the old terminology, the exiting cervical nerve can be compressed by a soft disk, hard disk or combination thereof. When conservative treatment fails, there are surgical options available that aim to increase the foraminal area to decompress the nerve root and relieve pain, numbness and/or weakness.

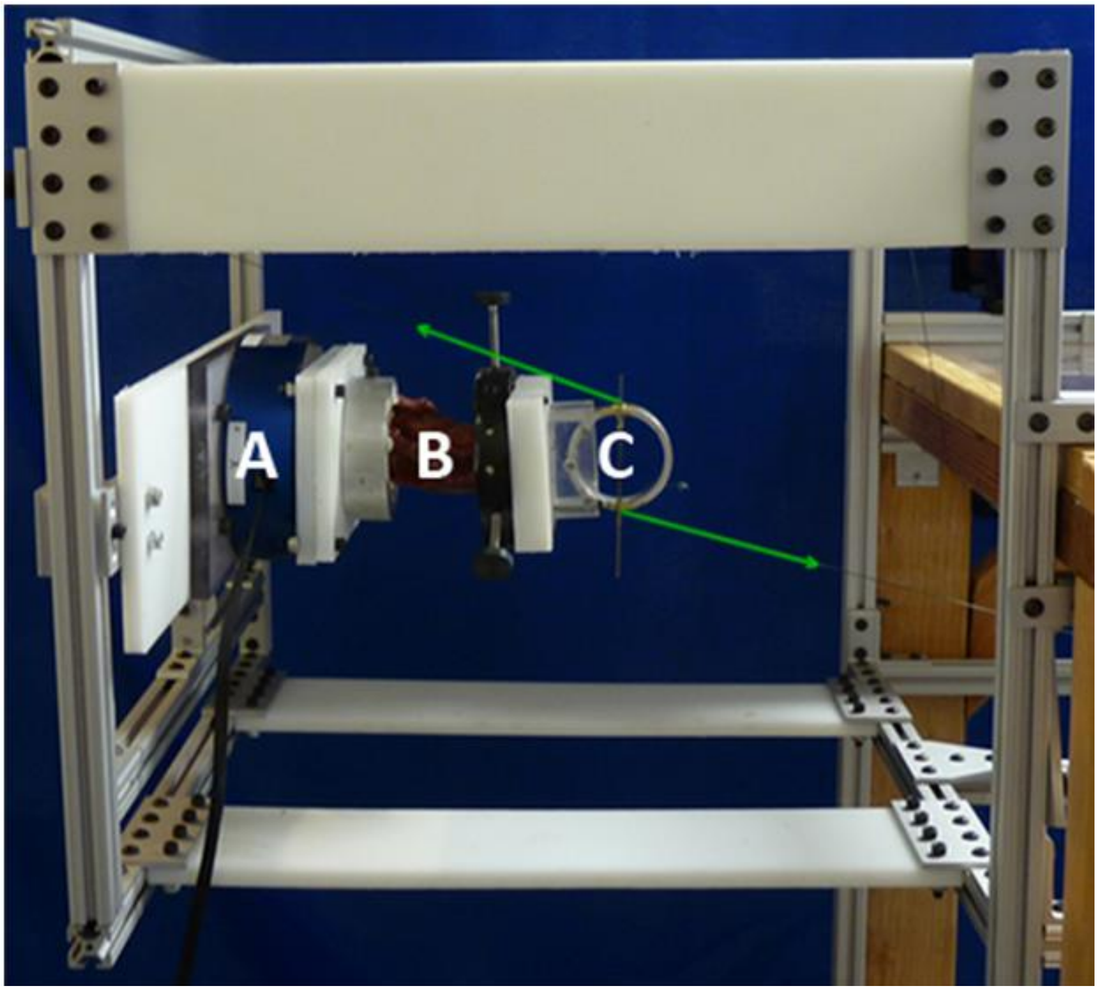

Figure 1: Biomechanical test jig to reproduce anatomical postures (neutral, flexion, extension). A) Load cell, B) Specimen, C) Pure moment fixture.

Anterior cervical discectomy and fusion (ACDF) is an established procedure originally described in 1955 by Robinson and Smith [1]. It has evolved to include a range of different techniques, including direct or indirect decompression of the uncovertebral joint, resection or preservation of posterior longitudinal ligament (PLL) and the use of a graft or cage in the intervertebral disc space. ACDF is appropriate in the presence of uncovertebral spurs and central disc herniations and is advantageous in that is does not necessarily need to expose the spinal canal [2,3]. Posterior keyhole foraminotomy (or laminoforaminotomy) (F) offers a less invasive alternative to an anterior approach and involves removing part of the superior articular facet to widen the neuroforamen. It is appropriate in patients with posterolateral soft disc herniation or osteophytic spurs originating from the facet joint, and is advantageous in that it involves adequate exposure of the nerve root, minimal laminoforaminotomy resection resulting in a limited affect on cervical spine stability, and possibly decreased morbidity and mortality [3,4,5,6]. Being a motion preserving procedure, keyhole foraminotomy can possibly have different implications on adjacent segment disease and the risk of reoperation, though there is no consensus on this topic either in the literature or among expert surgeons.

Both approaches have demonstrated consistent and excellent results, but to our knowledge, there have not been any studies comparing biomechanical or clinical outcomes of ACDF with posterior foraminotomy [1,2,4,7,8,9,10,11]. Additionally, there are technical details within the ACDF procedure that remain controversial, such as whether or not to directly resect the posterior part of the uncovertebral joint or its osteophytes and whether or not to remove the PLL. We aim to compare ACDF with and without direct uncovertebral joint resection (UVR) with posterior keyhole foraminotomy and determine which procedure most reliably increases the neuroforaminal area in different neck positions in a cadaveric model.

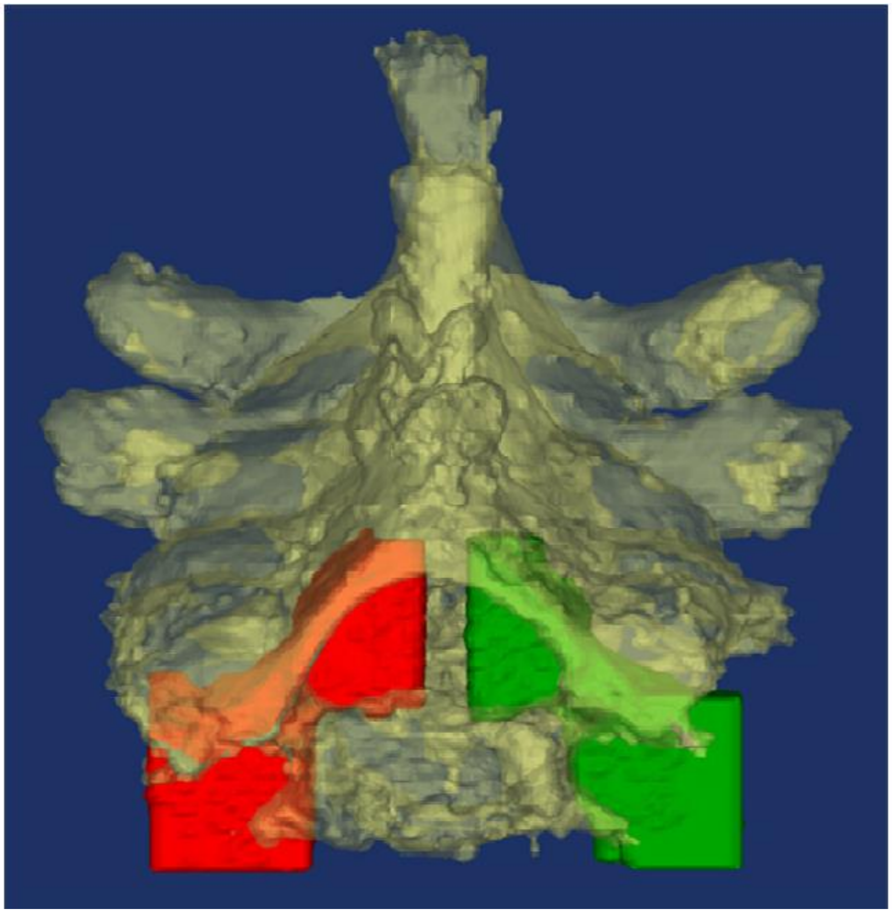

Figure 2: 3D model of right (red) and left (green) foramina for one level.

RESEARCH DESIGN AND METHODS

STUDY SPECIMENS

Eight cadaveric cervical functional spinal units (C5-C6 and C6-C7) from four cervical spines were tested and analyzed. All specimens were procured intact and fresh-frozen from national tissue banks. Mean age for all specimens was 73 years. Planar x-rays were taken of each intact spine using clinical-grade equipment (BV Pulsera, Philips). These images were examined by both the research engineer and a fellowship-trained spine surgeon.. Specimens with evidence of prior surgery, tumors, ankylosis or other bone deformities in the cervical region were excluded from the study. After radiographic examination, the lower cervical spinal section (C4-T2) was isolated. The cranial and caudal-most vertebrae were cast in shallow cups of quick-set resin (Smooth-Cast 300, Smooth-On) to facilitate loading through a biomechanical test jig (Fig. 1).

BIOMECHANICAL TESTING

The biomechanical test apparatus was modeled after a previously validated, non-constrained, cable-driven, pure moment device [12]. The specimen was fixed horizontally and subject to pure moment via a fixed ring-pulley system. A winch and turnbuckle were used to generate tension on cables, which was measured in real-time by a 6 axis load cell (JR3, Woodland CA) mounted to the test frame [Fig. 1]. To ensure minimal imaging interference, all parts of the frame directly in line with imaging trajectories were fabricated from radiolucent acrylic polymer. In the intact state and after each surgical procedure, each specimen was imaged in flexion/extension at 1.5 Nm and neutral position at 0 Nm. These loads are consistent with prior biomechanical tests of the cervical spine by our group [18-20] and others [12,13,15-17,21] and are safely within the non-destructive range.

SURGICAL METHODS

All functional spinal units underwent sequential decompression. Each unit was randomly assigned to a surgical sequence consisting of (1) bilateral F, (2a) ACDF, and (2b) ACDF+UVR. ACDF was performed with a 6 mm fibular strut allograft placed in neutral position and anterior plating (Synthes Spine). After the initial procedure—(1) or (2a) + (2b)—decompression by the other procedure was performed.

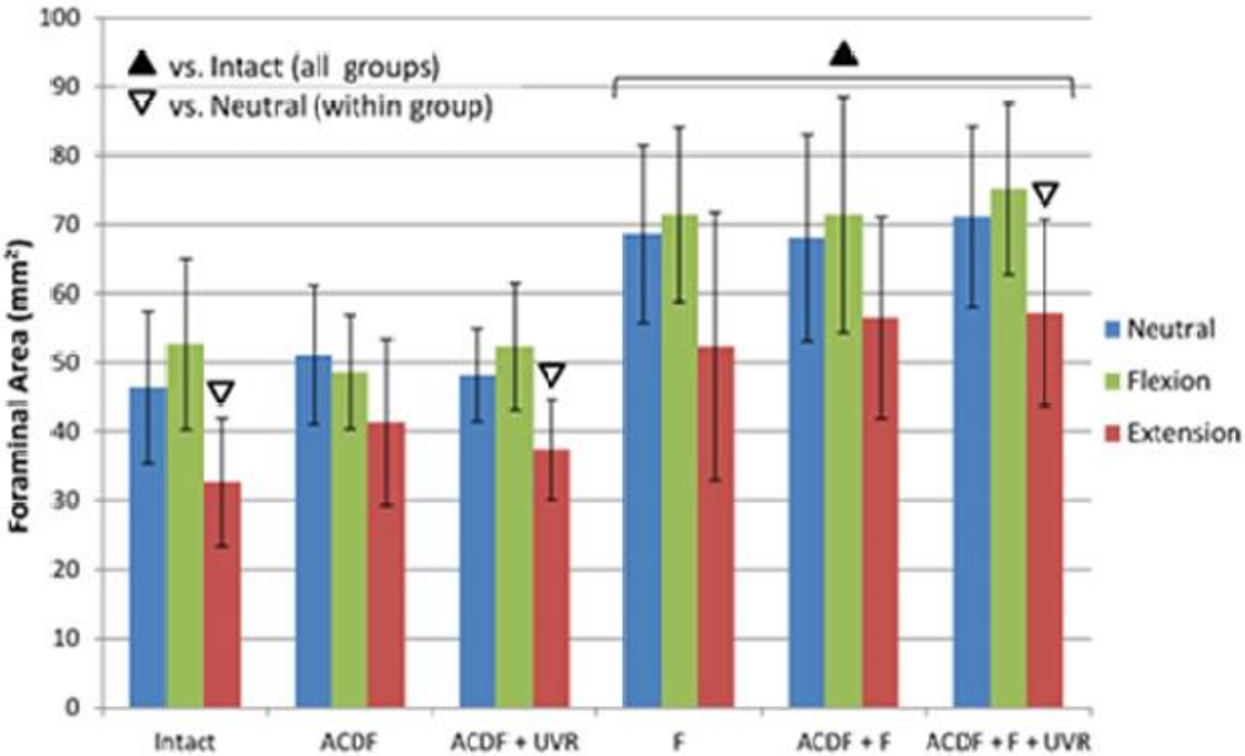

Figure 3: Comparison of six treatment groups in three loading conditions. Triangles represent statistically significant

POSTERIOR KEYHOLE FORAMINOTOMY

A three dimensional c-arm (Philips BV Pulsera) was used to confirm the correct vertebral level. The posterior musculature was dissected to expose the lamina and facets joints bilaterally with care to preserve the facet capsules. An interlaminar V was identified, and a high-speed burr was used to resect the overlying inferior articular facet to the lateral margin of each pedicle. Once the superior articulating facet was exposed, it was also resected to the lateral margin of each pedicle. The overall area of foraminotomy had approximately a 5-7 mm diameter. Special attention was made to resect no more than fifty percent of each facet joint. A nerve hook was used to palpate the lateral aspect of the cranial and caudal pedicles to ensure adequate resection [22].

ANTERIOR CERVICAL DISCECTOMY AND FUSION WITH INSTRUMENTATION

A two-level ACDF was performed, starting with the C5-C6 level. First, a 3-D C-arm was used to confirm the correct vertebral level. The exposed disc was incised and removed until the posterior longitudinal ligament and uncinate processes were visualized. Both the superior and inferior endplates were decorticated with a high-speed burr to create a flat surface on both sides. The specimen was placed in lordosis to distract the disc space. A fibular strut allograft—6 mm in height with parallel ends—was inserted into the disc space approximately 2 mm posterior to the anterior edge of the endplates. These steps were then repeated at C6-C7. A six-hole plate with six variable-angle screws was placed anteriorly to stabilize both levels.

After biomechanical testing, the anterior plate and screws were removed, as well as the fibular allograft. The posterior longitudinal ligament was then incised and resected Beginning at C5-C6, the posterior one-third of the uncinate process and uncinate spurs if any, were removed on each side to decompress both neuroforamens.. This step was repeated at C6-C7. The same fibular 6 mm allografts and six-hole anterior plate with cortical screws were placed [22].

DATA COLLECTION AND PROCESSING

3D X-ray sequences of each specimen were acquired in each anatomical posture (neutral, flexion, and extension) by a 3D C-arm (BV Pulsera, Philips) at a resolution of 0.7 x 0.7 x 0.7 mm. Images were then imported into medical image processing software (Mimics 15, Materialise). The neuroforamina of interest (left and right at C5-C6 and C6-C7) were isolated and recreated as 3D solid models [Fig. 3] using previously validated segmentation techniques [23]. Cross-sectional area orthogonal to each foraminal trajectory was recorded at 1 mm slice thickness intervals. Minimum cross-sectional area of each foramen was then extracted as the primary outcome measure for analysis. This image processing technique has been validated with an accuracy of 3.9% and repeatability of 1.6% in quantifying foraminal area.

DATA ANALYSIS

Six treatment groups were analyzed: Intact, F, ACDF, ACDF + UVR, ACDF + F and ACDF + F + UVR (N=16, 8, 8, 8, 8, respectively). The primary outcome measure was minimum cross-sectional area in all three positions (neutral, flexion, and extension). This outcome was assessed at both C5-C6 and C6-C7 for all treatment groups, with each foramen as its own control. One-way ANOVA was performed to determine any significant differences between treatment groups for each of three tested postures.

RESULTS

In the neutral neck position, the average neuroforaminal area for the intact specimens before any procedures had been performed was 46.3 +/- 11.0 mm^2. After ACDF, the average area increased to 51.1 +/- 10.1 mm^2, and after the addition of uncovertebral resection, the average area was found to be 48.2 +/- 6.7 mm^2. After foraminotomy, the average area increased to 68.6 +/- 12.9 mm^2, which was statistically significant ($p \leq 0.05$) when compared to the area of the intact specimens. The combination of ACDF and foraminotomy and ACDF with UVR and foraminotomy resulted in average areas of 68.1 +/- 15.0 mm^2 and 71.1 +/- 13.1 mm^2, respectively, both of which were resulted in significantly greater area than in intact specimens [Fig. 3].

In flexion, the intact specimens had an average neuroforaminal area of 52.7 +/- 12.4 mm^2, and after ACDF without and then with UVR, the areas were found to be 48.6 +/- 8.3 mm^2 and 52.3 +/- 9.2 mm^2, respectively. After foraminotomy, the average area increased a significant amount to 71.5 +/- 12.7 mm^2 when compared to the intact specimens in the flexed position. When ACDF and foraminotomy were combined, the average area increased to 71.4 +/- 17.1 mm^2, and when ACDF with UVR and foraminotomy were combined, the average area was 75.1 +/- 12.4 mm^2, both of which were significant [Fig. 3].

In extension, the intact specimens had an average area of 32.7 +/- 9.3 mm^2, which was a significant decrease in area when compared to the same intact specimens in neutral neck position. After ACDF, the area was an average of 41.3 +/- 12.1 mm^2. With the addition of UVR to ACDF, the area was significantly decreased (37.3 +/- 7.2 mm^2) when compared to the same specimens in neutral position. After foraminotomy and ACDF with foraminotomy, the average areas were found to be 52.3 +/- 19.4 mm^2 and 56.5 +/- 14.6 mm^2, respectively, both of which were significant increases when compared to intact specimens in extension. After ACDF with UVR and foraminotomy combined, the average area was 57.2 +/- 13.6 mm^2, which was a significant increase when compared to intact specimens in extension, but a significant decrease when compared to the same specimens in neutral neck position [Fig. 3].

DISCUSSION

Excellent clinical results have been demonstrated with posterior keyhole foraminotomy and ACDF for the treatment of cervical radiculopathy; however, this study is the first to directly compare the changes in neuroforaminal area between the two procedures [1,2,4,7,8,9,10,11]. Previous analyses of in vitro and in vivo changes in the cervical foramen with different neck positions have demonstrated that flexion increases foraminal area. Extension of the neck decreases the area, thus contributing to further compression of the exiting nerve root and an exacerbation of symptoms in extension (Spurling sign) [24,25,26,27]. Our data from cadaveric specimens supports these findings; flexion increased the area, but not to a significant degree, whereas extension did significantly decrease the neuroforaminal area by an average of 29.6% (average of 46.4 mm^2 in intact neutral to 32.7 mm^2 in intact extension).

While all procedures—including ACDF, ACDF + UVR, and foraminotomy—increased the neuroforaminal area, foraminotomy increased the area to the greatest extent and the most consistently, as it widened the area to a significant degree in all three neck positions. In our cadaveric specimens, foraminotomy increased the area in neutral by 48.0%, in flexion by 35.7%, and in extension by 60.2%. Most importantly, this increase in area seen in foraminotomy, as well as foraminotomy plus ACDF, was maintained in extension—the position where symptoms are the most severe—as there was not a statistically significant decrease in the area when compared to foraminotomy in neutral position. This also indicates that it is not a destabilizing procedure for the cervical spine. These findings support the study done by Chen, et al., who reported that posterior foraminotomy had little effect on the stability of the cervical motion segment when less than 50% of the facet joints were resected [6].

Previous literature clearly shows that ACDF produces excellent clinical results, but there is no clear understanding as to which aspect of the procedure contributes most to pain relief. In their review of eighteen patients who had undergone ACDF, Albert et al. revealed that there was no significant correlation between graft height and change in maximum foraminal area and postoperative relief of symptoms [28]. They concluded that indirect decompression by means of disc space distraction may not be the primary contributor to the clinical success of ACDF. Our results are consistent with this finding because although ACDF increased the neuroforaminal area in all three neck positions, it was not by a significant amount. In the neutral position, ACDF only increased the area by 10.1%. This would lead one to believe that it may be the direct decompression that is largely responsible for the pain relief. Shen at al. compared two patient groups that had either ACDF with indirect decompression by disc space distraction or direct uncovertebral joint decompression. They have found that the patients who had direct uncovertebral joint resection did not have any significant differences in outcomes when compared to the indirect decompression group. Both groups had good clinical results.

They concluded that direct uncovertebral resection was not necessary and only exposed the patient to further risks [29]. Our results support this finding as well, as we found that not only did the addition of the uncovertebral joint resection fail to increase the area, it also contributed to destabilizing the spinal unit (the area in extension significantly decreased when compared to ACDF + UVR in neutral)—a finding that has also been established in previous studies [30]. Though uncovertebral resection did not increase the area any further, partial resection of this joint can still be important for removal of soft disc herniations.

Thus, if both the direct uncovertebral joint resection and indirect decompression by disc space distraction do not significantly increase the neuroforaminal area in ACDF, then what is the mechanism for success of ACDF? It is possible that not much of an increase in foraminal area is needed for pain relief. Some believe that radiculopathy pain is actually a result of compressing the relatively small radicular artery. Additionally, it may be the stabilization of the spinal unit—by means of fusion and instrumentation—with resultant elimination of pathologic motion of the uncovertebral spurs that is an important aspect of the ACDF. Previous literature has also described how mechanical compression of a nerve can cause venous obstruction in the foramen, decreased blood supply to the nerve, leading ultimately to pain [31,32]. Therefore, another potential contributing factor is the improvement in the vascular supply to the exiting nerve root with subsequent relief of ischemic pain.

There are potential limitations to our study, including the small sample size of four cadavers, as well as the use of a single size fibular graft for all intervertebral disc spaces. A 6 mm graft was chosen for all intervertebral disc spaces in order to standardize the graft height. A previous study by An et al. determined that for a preoperative disc height of 3.5-6.0 mm, a graft size 2-3 mm greater than baseline was appropriate, as it resulted in the maximum incremental increase in foraminal height and area [33]. The average preoperative disc height in our specimens was 4.99 mm; therefore, either a 7-8 mm fibular graft or individually sized grafts for each disc space may have been more appropriate. Despite these shortcomings, our study is the first to directly compare the change in neuroforaminal area between posterior foraminotomy and ACDF +/- UVR.

CLINICAL IMPLICATIONS

Posterior keyhole foraminotomy and ACDF with or without uncovertebral resection can both be used to treat cervical radiculopathy. Keyhole foraminotomy is particularly useful for facet joint hypertrophy or posterolateral disc herniations, whereas ACDF has an important role in central disc herniations. Yet when deciding between the two, such as in cases of lateral disc herniation, the surgeon may consider a foraminotomy over ACDF, as our study demonstrated that this procedure produced the greatest increase in area in all three neck positions, and that this area was maintained in extension. Foraminotomy may also be considered as a salvage procedure in patients with persistent radiculopathy after a prior ACDF. Additionally, though resection of the uncovertebral joint in ACDF did not demonstrate any increase in area, it can still have a role in removal of soft disc herniations. Our findings pertain primarily to bony stenosis and may not apply to soft disc pathology.

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