Review Article

Foraminal height measurement techniques

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Background: One of the proposed advantages of anterior lumbar interbody fusion (ALIF) is restoration of disc height and hence an indirect foraminal height restoration. While this proposed advantage is often quoted in the literature, there are few robust studies demonstrating restoration of foraminal volume. Thus, this study aimed to review the literature and discuss the progression and development of foramen measurement techniques.

Methods: A review of the literature was performed to identify studies which reported foraminal height and dimensions following fusion surgery in cadaveric models or patients.

Results: Techniques in prior studies used to quantify foraminal dimensions before and after fusion operations include analysis from plain radiographs, computed tomography (CT) scans and magnetic resonance imaging (MRI) scans. Recent studies have attempted to standardize foraminal dimension measurements with the use of orthogonal software, accelerator-based measurements and the use of multiple images for three-dimensional reconstruction of the foramen volume.

Conclusions: Consistent results have demonstrated significant increases in foraminal area and height following anterior lumbar interbody distraction, providing evidence that ALIF can indirectly increase foraminal height. Future studies should use standardized measurement approaches such as the Pedicle-to-Pedicle technique with CT or MRI images to determine changes in foraminal dimensions.

Keywords: P-P technique; foramen measurement; indirect decompression; anterior lumbar interbody fusion (ALIF); disc height; fine cut computed tomography (CT)

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Introduction

Surgical interbody fusion has been found to be an effective method of treatment for debilitating back pain (1-3). Interbody fusion has the potential advantage of removing the disc as a source of pain (4). Many methods of fusion are available to contemporary spine surgeons, of which one of the options is the anterior lumbar interbody fusion (ALIF) technique. A primary consideration of such a fusion technique is the restoration of normal anatomy, including foraminal area, disc height, lumbar lordosis and sagittal balance (5,6). Failure to restore these parameters can result in permanent loss of lordosis and sagittal balance, leading to poorer long-term outcomes (7,8).

One of the proposed advantages of ALIF is restoration of disc height and hence an indirect foraminal height restoration. While this proposed advantage is often quoted in the literature, there are few robust studies demonstrating restoration of foraminal volume. Techniques in prior studies used to quantify foraminal dimensions prior and after fusion operations include analysis from plain radiographs, computed tomography (CT) scans and magnetic resonance imaging (MRI) scans. Recent studies have attempted to standardize foraminal dimension measurements with the use of orthogonal software, accelerator-based measurements and the use of multiple images for three-dimension reconstruction of the foramen volume (4,9-16).

In the present article, a review of the literature using recommended guidelines (17,18) was performed to assess the changes in foraminal volume and dimensions with ALIF procedures.

Measurement techniques

The included study characteristics and baseline pre-operative foraminal dimensions are summarized in *Table 1* and *Table 2*.

Mold-based measurements

One of the earliest studies of foraminal dimension measurements was that reported by Stephens *et al.* (16) in 1991. This group investigated foraminal shape and area using 20 cadaveric spine models. Following the removal of all muscle and associated loose connective tissue, the vertebral column with the major ligaments still retained was assessed quantitatively using the mold technique. Stephens *et al.* (16) used cotton wool doused in silicon rubber and imprinted this pliable material onto the foraminal region, allowing it to set to cast at room temperature. The cast mould was then removed from the foraminal space and sectioned to create an accurate representation of the foraminal volume. Subsequently, the cast is dabbed in ink and the faces of the cast volume are printed on paper, allowing quantification of dimensions. The foraminal height was defined as the maximal diameter of the prints, whilst the foraminal width was defined as the widest measurement perpendicular to the height. This technique was validated in this study by comparison to interpedicular heights measured on radiographs, defined as the distance between the lower margin of the upper pedicle to the upper margin of the lower pedicle. Using the mold technique, Stephens *et al.* reported average foraminal area of 101.6 mm^2 (range 40-160 mm^2) and average foraminal height of 14.9 mm (range 10-19 mm). Subgroup analysis demonstrated that the shape of the foraminal space was altered by disc degeneration, from a round to auricular shape.

Chen *et al.* (10) also employed a variant of the silicon mold technique. Silicon rubber was used to fill the neuroforaminal space and allowed to set, creating an exact mold of this volume. In contrast to Stephens *et al.*, Chen *et al.* injected their silicon mold with methylene blue, a dye which provided visual markers of the lateral and medial borders of the foraminal space. Subsequently, the mold was taken out and trimmed down to the precise borders defined by the methylene blue dye. From the mold, the foraminal height and width could be measured. To determine the foraminal volume, the authors used the mathematical relationship between density, volume and mass of silicon, where the density was defined as 1.05 g/cm^3. In tandem with another measurement technique, Chen *et al.* demonstrated that following anterior interbody distraction using a BAK cage implant, there was a 28.5% increase in foraminal area at the L4-L5 level and 26.4% increase in foraminal area at the L5-S1 level. Foraminal volume was also increased by 22.9% (L4-L5) and 21.5% (L5-S1) following a simulated ALIF procedure on a cadaveric spine model.

Caliper-based measurement

Another technique used in early foraminal volume quantification studies involves the use of calipers directly on the foraminal space. Schlegel *et al.* (9) reported a 37.2% increase in foraminal area using caliperic method and sagittal CT scans (at middle of the pedicle) after distracting the disc space. Besides the mold technique, Chen *et al.* utilized the Blunt Probe technique, where probes of different sizes were placed into the neuroforamen without distraction. Essentially a variant of the caliper approach, the Blunt Probe technique used finely graded circular blunt probes, of which the largest diameter probe that was able to pass through the neuroforamen without forced distraction was recorded and used to determine the neuroforaminal area.

More recently, Torun *et al.* (19) used an electronic digital caliper with sensitivity of 0.1 mm. Measurements were performed by three neurosurgeons and crossed checked with measurements performed by an experienced anatomist. From their quantification, Torun *et al.* reported mean foraminal height of 19.4 mm from 15 cadaveric spine models.

Wang *et al.* (11) employed a similar method called a Cement Mold technique which used a 3-D Gel Instant Molding Compound. However the mold created, according to the shape of the neuroforamen, was pressed on to recording paper to create a digital imprint and therefore may have been subject to deformations. Digital imaging software was employed to calculate foraminal height and cross-sectional area. They found ALIF with tapered and cylindrical cages improved foraminal area by 17 % and foraminal height by 9%.

Radiographic methods

Hsieh *et al.* (4), who compared the difference between

Table 1 Study characteristics, outcomes, and foraminal dimension measurement technique

First author	Year	Country	Type of subject	Number	Intervention	Outcomes measured	Method of measurement
Stephens	1991	UK	Cadavers	20	Removal of all muscle and associated loose connective tissue, but major ligaments retained	Foraminal shape, foraminal area	Molding technique: cotton wool with silicone rubber was used to take molds of intervetebral foramen. The cast is then used with ink to produce a "stamp" in print. This is then used to measure foraminal area and width
Schlegel	1994	USA	Embalmed human lumbosacral cadaveric spines	10	Resection of disc and ligamentous structures, followed by anterior distraction using 5 mm or 10 mm intradiscal spacers	Foraminal area, canal area	Foraminal space measured using direct caliperic method and via sagittal reconstruction of CT scan at midportion of pedicle on axial cut. Orthogonal software was used for quantification
Chen	1995	USA	Cadaver: 9 fresh frozen degenerative cadaver lumbar spines, stored at −20 ℃ until testing	9	Anterior interbody distraction using BAK implant	Anterior disc height, posterior disc height, pre and post op	Blunt Probe technique: probe is placed through the neuroforamen without distraction of the facet joint. It can then calculate the foraminal area. Silicon mold technique: mold created from neuroforamen, which was then injected with methylene blue. After obtaining the cast and removing excess sections, its volume and dimensions can be measured
Inufusa	1995	USA	Cadaveric spines	19	NA	Foraminal height, foraminal width, posterior disc height, foraminal area	Frozen cadaveric spine specimens were sliced using cryomicrotome in the sagittal plane. Sagittal CT obtained at the middle of the pedicle, then used to estimate dimentions of foramen and canal, with flexion and extension movements
Torun	2006	Turkey	Cadaveric spines	15	NA	Foraminal height, forminal width, diameter of nerve root	All measurements were made using an electronic digital caliper with a sensitivity degree of 0.1 mm. Measurements were performed by 3 neurosurgeons and 1 anatomist, and cross-checked
Hsieh	2007	USA	Patients who required ALIF, with minimum follow-up of 24 months	32	Open ALIF with instrumentation, except in the cases of patients without instability	Anterior disc height, posterior disc height, foraminal height, local Cobb angle, lumbar lordosis	Radiographs were obtained preoperatively and at follow-up. Anterior disc height was measured as distance between inferior endplate to superior endplate at anterior vertebral body line, and posterior disc height measured at vertebral body line. Foraminal height was measured as distance between inferior pedicle wall to superior pedicle wall of the level below

Table 1 *(continued)*

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First author	Year	Country	Type of subject	Number	Intervention	Outcomes measured	Method of measurement
Wang	2007	USA	Bovine calf spine model	16	ALIF	Foraminal area, foraminal height, without and with dynamic loading	Preoperative and postoperative MRI was obtained. The foramen was modelled as an ellipse, and the width and height of the ellipse was calculated. For patients who also had digital images available, orthogonal software could be used to quantify the area of the shape for the foramen
Karahalios	2010	USA	Human cadaveric L3-S1 specimens	7	ALIF	Mean foraminal height	3D detecting software to calculate angles of the coordinates of a specimen motion. Points representing rostral and caudal vertices of L4L5 foramina were identified and used for quantification of height and changes
Cho	2012	USA	Patients needing ALIF followed by posterior pedicle screw fixation without distraction or foraminotomy	26	ALIF followed by posterior pedicle screw fixation without distraction or foraminotomy	Preoperative and postoperative foraminal area	From MRI images, foramen was modeled as an ellipse. Height and width of ellipse were measured to provide dimensions
Kepler	2012	USA	Patients requiring LTIF	29	LTIF	Foraminal area, average disc height anterior and posterior	CT were obtained preoperatively and at follow-up. Anterior disc height was measured as distance between inferior endplate to superior endplate at anterior vertebral body line, and posterior disc height measured at vertebral body line. Foraminal height was measured as distance between inferior pedicle wall to superior pedicle wall of the level below
Shin	2013	Korea	Patients with isthmic spondylolisthesis requiring ALIF	40	Microscopic anterior foraminal decompression during ALIF followed by percutaneous posterior fixation	Foraminal height, foraminal width, foraminal area	CT images were obtained preoperative and postoperatively. Measurement was performed via 2D reconstruction of sagittal image at mid-portion of the foramen to obtain foraminal dimensions
Rao	2015	Australia	Patients requiring ALIF	140	ALIF	Foraminal area, height, width, anterior disc height, posterior disc height, local disc angle, lumbar lordosis	P-P pedicle to pedicle technique was designed to standardize the measurement of the foramen. CT scans were aligned in all three dimensions: parallel in axial plane, along midline of both pedicles, and along midline of both pedicles in the coronal plane and in sagittal plane perpendicular to the disc space. Analysis was performed using Image J

ALIF, anterior lumbar interbody fusion; LTIF, lateral transpsoas interbody fusion; CT, computed tomography; MRI, magnetic resonance imaging.

Table 2 Baseline measurements of foraminal and disc dimensions

First author	Number	Foraminal area (mm^2)	Foraminal height (mm)	Anterior disc height (mm)	Posterior disc height (mm)	Cobb angle (deg)	Lordosis (deg)
Stephens	20	101.6±24.4	14.85±1.85	NR	NR	NR	NR
Schlegel	10	166±26.7	NR	NR	NR	NR	NR
Chen	9	NR	NR	12.1±3.3 mm (L4-L5); 11.2±2.9 mm L5S1	6.3±1.5 mm (L4-L5); 5.3±1.3 mm L5S1	NR	NR
Inufusa	19	108.8±27.3	17.7±3	NR	5.7±2.3	NR	NR
Torun	15	NR	19.4±2.7	NR	NR	NR	NR
Hsieh	32	NR	19.7	10.9	6.4	7.1	50.4
Wang	16	190.8 (tapered), 168 (cylindrical)	22 (tapered), 21.3 (cylindrical)	NR	NR	NR	NR
Karahalios	7	NR	15.50±2.97	NR	NR	NR	NR
Cho	26	87.03±30.36	NR	NR	NR	NR	NR
Kepler	29	103±27.5	NR	6±3.5	3.9±3.9	NR	NR
Shin	40	Osteophyte group: 94.5±16.56; disc herniation: 103.26±15.82	Osteophyte group: 14.32±2.13; disc herniation group: 16.7±2.42	NR	NR	NR	NR
Rao	140	90	140	83±31	48±22	5.9±3.9	41.8±11.3

NR, not reported.

ALIF and transforaminal lumbar interbody fusion (TLIF), reported an 18.5% increase in foraminal height following an ALIF. Plain radiographs were taken preoperative and postoperative in order to measure the disc parameters and foraminal dimensions. Anterior disc height was defined as the distance between the inferior to superior endplate at the anterior vertebral body line. The posterior disc height was measured similarly at the vertebral body line. Similarly to prior studies, the foraminal height was measured as the distance between the inferior pedicle wall to superior pedicle wall of the level below. Although ALIF was superior to TLIF in restoring foraminal height, disc height and local disc angle, there was no difference in clinical outcome at 2 years.

CT based measurements

Schlegel *et al*. (9), in conjunction with their direct caliperic technique, also used sagittal reconstruction of CT scans at the midportion of the pedicle on axial cut. Orthogonal software was utilized for accurate computer-based measurements of the foraminal area and canal area in 10 embalmed human lumbosacral cadaveric spines. Schlegel simulated ALIF interventions by resecting disc and ligamentous structures, followed by anterior distraction using 5 mm or 10 mm intradiscal spacers. Significant increases in foraminal area were noted (40%) following anterior distraction.

Inufusa *et al*. (12) used 19 frozen cadaveric spine specimens, which were then sliced using cryomicrotome in the sagittal plane in order to study the dimensions of the neuroforamen. The actual dimensions were measured using a sagittal CT scan at the level of the middle of the pedicle. The goal of the study was to look at changes in foraminal and canal dimensions with flexion and extension. At rest, the foraminal area was reported to be 108.8 mm^2 and foraminal height was reported as 17.7 mm, consistent with values reported in prior cadaveric studies.

Kepler *et al*. (15), when measuring foraminal volume change in lateral transpsoas interbody fusion (LTIF) cases, used CT scans to measure the foraminal area but no standardized technique was used. CT images were obtained preoperatively and postoperative at follow-up. Similar to prior radiographic and CT based measurement studies, the anterior disc height was defined as the distance between the inferior and superior endplates at the anterior vertebral body line, whilst posterior disc height was measured at the vertebral body line. From CT scans of 29 patients, there was a 35% increase in foraminal area at the L4-L5 level. Significant increases in anterior disc height (65%) and posterior disc height (61.5%) were also noted.

Similarly, Shin *et al*. (6) used CT images obtained preoperative and postoperatively to calculate the foraminal height, width and area. Two-dimensional reconstructions of the sagittal image were performed at the mid-portion of the foramen, before and after ALIF and percutaneous posterior fixation. In their study, patients were subgrouped into indications, osteophyte induced and disc herniation. In the osteophyte group, there was a 41.8% increase in foraminal area and 36.4% increase in foraminal height to 19.5 mm. In the disc herniation group, foraminal area increased by 38% to 142.7 mm^2, whilst foraminal height increased 25% to 20.87 mm.

MRI based quantification

Cho *et al*. (14) used MRI scans to measure the foraminal area preoperatively and postoperatively with ALIF surgery. Sagittal images from printed films or on the Vitrea (imaging software) were utilized. The foraminal space was modelled as an ellipse shaped, and the height and width of the foraminal space was then deduced using known mathematical formulations for the short and long diameters of ellipses. Foraminal dimensions were determined preoperatively and postoperatively following an ALIF procedure with posterior pedicle screw fixation performed on 26 patients. Cho *et al*. reported a significant increase in foraminal area to 124.7 mm^2 (43.3%).

For a select group of patients in the study by Wang *et al* who had digital images, orthogonal software was utilized to determine the area of the foramen shape, without need to model this as an ellipse. However, similar results were reported by both techniques.

Accelerometer based measurements

Another method included that employed by Karahalios *et al*. (13), which used 3D motion detecting software to calculate angles of the coordinates of specimen motion in describing the spine's angular motion. The points representing the rostral and caudal vertices of the left and right L4/5 foramina were then identified with the help of a digitizing probes and rigid-body methods, and were used in quantifying foraminal height and changes. The goal of this study was to look at stability provided by interspinous clamp compared to ALIF. A 4.9% increase in foraminal height was reported in cadavers with ALIF only, compared with 11.6% in cadavers undergoing ALIF with plates, and 7.7% increase using ALIF with bilateral screws.

Pedicle-to-pedicle quantification

Recently, the first clinical study to quantify foraminal dimensions using a standardized approach with three-dimensional CT scans before and after ALIF in 140 patients was published. Rao *et al*. (20) analysed CT scans in maximum intensity projection format. A new pedicle to pedicle (P-P technique) technique was designed to standardize the measurement of foramen, which involved aligning the CT scans in 3 dimensions; parallel in axial plane, along the midline of both the pedicles in the coronal plane and in the sagittal plane perpendicular to the disc space. The snapshot of the foramen so obtained was measured using Image J. From this, foraminal area, height and width could be quantified. This technique was also used to measure anterior and posterior disc height, as well as lumbar lordosis and local angle. From scans of 140 patients with 184 levels, the authors reported increased foraminal area (67%), foraminal height (21%) and width (38%). There were also significant improvements in anterior disc height (90%), posterior disc height (77%), and lumbar lordosis (6%). High intra- and inter-class reliability was demonstrated.

Overall, all studies regardless of technique demonstrated significant increases in foraminal area and foraminal height following fusion procedures (*Table 3*). The increase in foraminal area ranged from 15.6% to 67%, whilst the increase in foraminal height ranged from 4.9% to 36.4%. The variation in percentage of increase is like to due to various factors including: (I) the differences in anatomy between humans and cadaveric models; (II) ALIF or anterior procedure performed, and whether plates or posterior screw fixation was performed or not; (III) different shape and size cages used, e.g., tapered *vs*. cylindrical; and (IV) the inherent differences among measurement techniques employed.

Progress in measurement techniques

As per the literature presented, there are very few studies

Table 3 Percent changes in foraminal and disc dimension measurements following fusion

First author	Intervention	Δ Foraminal area (%)	Δ Foraminal height (%)	Δ Anterior disc height (%)	Δ Posterior disc height (%)
Schlegel	ALIF	25.8%	NR	NR	NR
Chen	ALIF	28.5% (L4-L5), 26.4% (L5-S1)	NR	35.2% (L4-L5), 24.8% (L5-S1)	37.1% (L4-L5), 4 5.1% (L5-S1)
Hsieh	ALIF	NR	18.5%	65.1%	34.4%
Wang	ALIF	17.7% (tapered), 15.6% (cylindrical)	12.3% (tapered), 8.5% (cylindrical)	NR	NR
Karahalios	ALIF	NR	4.9% (standalone), 17.0% (plates), 7.7% (bilateral screws)	NR	NR
Cho	ALIF	43.3%	NR	NR	NR
Kepler	ALIF	35.0%	NR	65%	61.5%
Shin	ALIF	42.1% (osteophyte), 38.1% (disc herniation)	36.4% (osteophyte), 25.0% (disc herniation)	NR	NR
Rao	ALIF	67%	21%	90%	77%

ALIF, anterior lumbar interbody fusion; NR, not reported.

which have measured lumbar foramen areas or heights. Most of the studies have been performed in spine cadaveric models (9,10,12,13,16,19), and of the few clinical studies available, a standardized technique of measuring the foramen values was not employed. Clinical studies have shown significant improvement in foraminal measurements after ALIF (6,15). None of the clinical studies have looked at the effect of restoration of disc height parameters on foraminal area restoration. But this has been elegantly demonstrated in a cadaveric study by Schlegel *et al.* (9), which showed that a 10 mm distraction of disc can result in 40% foramen area improvement.

Initial studies used relatively crude techniques of direct caliper, probes or creation of molds to estimate the foraminal space dimensions. Whilst advocates of this approach argue that the use of a penetrating caliper or probe may stimulate the functional relationship between nerve and foramen, ultimately, measurements are not recorded using a digitized approach and the instruments themselves have poor sensitivity. Recent studies have used advanced versions of these tools, including electronic calipers, in an attempt to obtain more accurate quantification of foraminal height and width.

Following this, studies started to use clinical images, in the form of radiographs, CT and MRI scans. The use of radiographs has proved to be inadequate, given that this approach does not account for the change in orientation of the foramen dependent on the depth of the radiograph. More specifically, the foramen changes orientation from almost horizontal to anterocaudal, moving from upper lumbar to the lumbosacral junction. Compared to radiographs, CT offers better definition and images of soft tissue and bone of the foramen. There are several limitations with this technique. Firstly, many CT images are obtained on supine patients, which may underestimate the foraminal area compared to standing patients undertaking radiographs. Secondly, the majority of studies employing CT imaging for foraminal measurements have done so using single orientations. Despite the study by Shin *et al.* measuring all foraminal dimensions, this investigation only created a two-dimensional reconstruction. The more recent study by Rao *et al.* (20) addressed the issue of non-standardized quantification from CT images by using images obtained by three dimensions (Pedicle-to-pedicle technique), which were then aligned to reconstruct the foraminal space.

MRI can also be used for determining foraminal measurements. MRI can provide a more detailed and accurate foraminal shape compared to CT images. Potential limitations may include the fact that artefacts will show up more compared to CT, especially following instrumentation. Similarly to CT, the use of MRI images of single orientations is not standardized, which may increase the heterogeneity of reported measurements (21).

Advances in technology have led to one study (13) using an accelerometer-based technique for analysis of the foraminal dimensions. This technology would be particularly useful in measuring real-time changes in foraminal dimensions, such as during flexion and extension movements, and changes in angulation.

Conclusions

In summary, various measurement techniques have been used in the literature for quantification of foraminal dimensions. Consistent results have demonstrated significant increases in foraminal area and height following anterior lumbar interbody distraction, providing evidence that ALIF can indirectly increase foraminal height. Future studies should use standardized measurement approaches such as the Pedicle-to-Pedicle technique with CT or MRI images to determine changes in foraminal dimensions.

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Footnote

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