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ORIGINAL ARTICLE

Influences of different lower cervical bone graft heights on the size of the intervertebral foramen: multiple planar dynamic measurements with laser scanning

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Abstract

The aim of this study is to evaluate the influences of different bone graft heights on the size of the intervertebral foramen, which will help determine the optimal graft height in clinical practice. Six fresh adult cadavers were used, with the C5-C6 vertebral column segment defined as the functional spinal unit (FSU). After discectomy, the C5/6 intervertebral height was set as the baseline height (normal disc height). We initially used spiral computed tomography (CT) to scan and measure the middle area of the intervertebral foramen when at the baseline height. Data regarding the spatial relationship of C5-C6 were subsequently collected with a laser scanner. Grafting with four different sized grafts, namely, grafts of 100, 130, 160, and 190% of the baseline height, was implanted. Moreover, we scanned to display the FSU in the four different states using Geomagic8.0 studio software. Multiple planar dynamic measurements (MPDM) were adopted to measure the intervertebral foramen volume, middle area, and areas of internal and external opening. MPDM with a laser scanner precisely measured the middle area of the intervertebral foramen as spiral CT, and it is easy to simulate the different grafts implanted. With the increase of the bone graft height, the size of the intervertebral foramen began to decrease after it increased to a certain point, when grafts of 160% of the baseline height implanted. MPDM of the intervertebral foramens with laser scanning three-dimensional (3D) reconstitution are relatively objective and accurate. The recommended optimal graft height of cervical spondylosis is 160% of the mean height of adjacent normal intervertebral spaces.

Keywords Laser scanning 3D reconstruction · Multiple planar dynamic measurements · Cervical spondylosis · Lower cervical spine · Intervertebral foramen · Bone graft height

Introduction

Cervical spondylosis of the nerve-root-type is characterized by nerve root involvement (compression, retraction, and inflammation) and dysfunction of the corresponding nerve innervated areas. The cervical nerve root sleeve consists of three parts, namely, the inside (vertebral pedicle), middle part (vertebral artery), and outside. The inside part is particularly important and directly related to the pathogen of nerve-root-type cervical spondylosis because it lies in the intervertebral foramen, with the uncovertebral joint in front of it and the facet joint behind it, and it is most likely to be narrowed and compresses the nerve. Therefore, the main surgical purposes include restoration of the intervertebral foramen size and removal of the compression on nerve roots.

Substantial clinical practice and research have demonstrated that intervertebral bone graft fusion is necessary to restore the foramen and maintain the cervical stability. However, there is no universally accepted standard regarding the optimal bone graft height. In clinical work, most surgeons decide the size of the bone graft based on their own experience. This

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approach may cause problems, such as a small graft, delayed fusion and graft dislodgement, and thus suboptimal recovery of the intervertebral space height, which directly compromises the surgical results. Moreover, over-high grafts are difficult to place and may easily cause a torn ligament and capsule, as well as spinal cord injury [1]; the increase of compressed stress on the upper and lower endplates results in a higher incidence of complications, including a collapse of the bone graft and fracture of the upper and lower endplates.

Without question, the intervertebral foramen size is an important indicator for the bone graft height. Currently, radiologists measure the size of the intervertebral foramen with computed tomography (CT), three-dimensional (3D) reconstitution by volume rendering (VR), or multi-planar reconstitution (MPR). Nevertheless, this method requires manual delineation of the intervertebral foramen with a mouse. High precision always requires repeat testing by numerous radiologists. Laser scan techniques have been reported by several studies, such as Wu et al. [2] who combined a laser scan and reverse engineering software to build the titanium complete denture plat. Moreover, laser has also been used in orthopedics. Sotsuka et al. [3] performed a bone osteotomy with the ytterbium-doped fiber laser to assess the histological appearance of the bone ablation and healing response. Thus, in the current study, we combined laser scanning 3D reconstitution and multiple planar dynamic measurements (MPDM), the latter of which may well simulate various changing progresses, such as degeneration development or interbody grafting. It is called "dynamic," so named that the objective measurement of a fixed section of the same intervertebral foramen is available when the intervertebral space height is changing. With this method, we further precisely evaluated the influence of different graft bone heights on the intervertebral foramen, which will subsequently provide clinical reference for the graft height after cervical anterior decompression.

Materials and methods

Specimens and experimental model

The Institutional Human Investigation Committee of Sun Yat-sen Memorial Hospital, Sun Yat-sen University, approved the experimental protocol. All procedures performed in the studies involving specimens were conducted in accordance with the ethical standards of the institutional or national research committee, as well as the 1964 Helsinki declaration and its subsequent amendments or comparable ethical standards. Six fresh-frozen human cadaver cervical spines (C1-T1) were obtained from the Department of Anatomy, Nanfang Medical University, China. All subjects were victims of acute cranial injuries and had no history of orthopedic disorders. They died at the ages of 24–53 years (average 29 years).

In the present study, we defined the C5-C6 segment as a functional spinal unit (FSU). We performed the X-ray prior to sampling to ensure that there is no obvious sign of degeneration (particularly disc height collapse) at C4/5, C5/6, and C6/7 and to exclude fractures, osteolytic lesions, previous fusion surgery, or other abnormalities. We precisely measured the anterior and posterior heights of C4/5, C5/6, and C6/7 disc spaces from the lateral X-ray. We calculated the average values of anterior and posterior heights as the disc height. In the clinic, we always estimated the original disc height of the degenerated intervertebral space according to the adjacent normal intervertebral spaces. We thus defined the baseline height of C5/6 as the mean disc space height of C4/5 and C6/7.

Soft tissues other than the joints, ligaments, articular capsules, and longuscolli were removed. The superior articular surface and the upper endplate of C5 were fully exposed, as were the inferior articular surface and the lower endplate of C6. We subsequently conducted surface spraying with white pigment. The specimens were thawed naturally for 10 h prior to the experimental procedure. Standard discectomy at C5/6 and Smith-Robinson grafting was performed.

Computed tomography (CT) scan and measurement

We initially used CT (HiSpeed, GE, Fairfield, USA) to scan the specimens of the baseline height state. We subsequently uploaded the cross-sectional images to the work station (AW4.0, GE, Fairfield, USA) and measured the intervertebral foramen area with volume analyze software, including VR and MPR.

VR: The 3D image was freely rotated and fixed at the angle that best showed the intervertebral foramen. MPR: The middle point of the C6 vertebral arch was located on the transverse image, and a line was made parallel to the long axis of the vertebral arch; the middle region of the intervertebral foramen was subsequently obtained from the sagittal reconstruction. We manually delineated the intervertebral foramen with a mouse and obtained the middle area of the intervertebral foramen values using the automatic software analysis. Three radiologists independently tested the intervertebral foramens and calculated the mean values (standard deviation < 10%).

MPDM with laser scanning 3D reconstitution

The working state of the 3D laser scanner (Optix 400, 3D Digitla Corporation, Sandy Hook, USA) is presented in Fig. 1. The four states of the C5-C6 FSU, namely, grafts of 100, 130, 160, and 190% of the baseline height implanted, were separately recorded with the 3D laser scanner and Realscan USB software. Under each state, we must obtain the point cloud images of the superior articular surface and the upper endplate of C5 and the inferior articular surface and

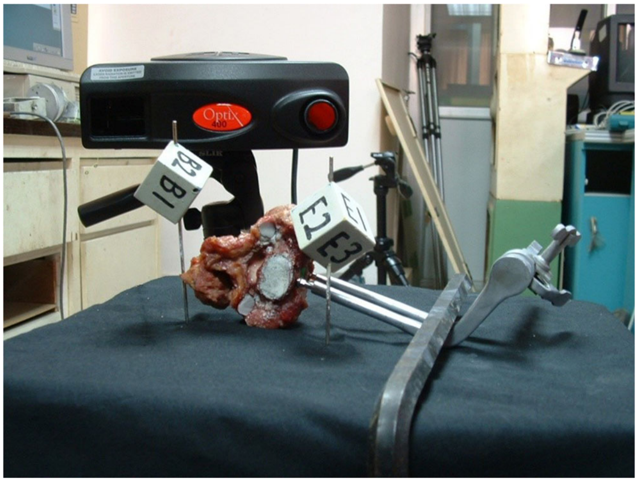

Fig. 1 Working state of the 3D laser scanner. The superior articular surface and the upper endplate of C5 and the inferior articular surface and the lower endplate of C6 were scanned to collect spatial information of C5-C6 FSU, in which the surface was sprayed with white pigment

the lower endplate of C6, which was sprayed with white pigment beforehand. These images were used to regenerate the spatial relationships of C5 and C6 in the four states, which subsequently served as the markers for 3D reconstitution. Then, the C5 and C6 vertebrae were anatomized only for the bone structure, and the vertebral surface data were obtained from an overall and multi-perspective scan. Using the scanning data of the spatial relationship between C5 and C6 and the single vertebral surfaces, the C5-C6 FSUs under baseline height were 3D reconstituted and analyzed through the point-clouds registration using Geomagic8.0 studio software (Geomagic, Research Triangle Park, USA). In the same manner, we restored C5-C6 FSU states using different implanted heights.

Statistical analysis

All data were expressed as the mean and standard deviation. A P value of less than 0.05 was considered a statistically significant difference. According to the results of the homogeneity test for variance, an independent or paired samples t test was applied to compare the differences in the intervertebral foramen between the two groups. One-way ANOVA was employed to compare the four states using the Statistical Product & Service Solution 13.0 (SPSS, Chicago, USA).

Results

X-rays of the six fresh-frozen human cadaver cervical spines are presented in Fig. 2a, b. The results indicated that the baseline height, which was defined as the average of adjacent disc heights, could replace the original height of the degenerative space when this level was collapsed. We calculated that the mean C5/6 disc space height of the six experimental models was 5.33 ± 0.44 mm, whereas the mean baseline height was 5.38 ± 0.49 mm. According to the paired samples t test ($t = 0.155$, $P = 0.880$), there was no significant difference between the measurement methods.

The C5-C6 FSUs with baseline height were 3D reconstituted as shown in Fig. 3a, b. In the same manner, the states with grafts of 100, 130, 160, and 190% of the baseline height implanted were reconstituted, as shown in Fig. 4a–d, respectively. Then, the internal, middle, external area, and volume of the intervertebral foramen were measured on four states. Figure 5 presents how the coordinate system was established. First, we made the Y-axis across the center of the lateral axis of the C6 vertebral pedicle and kept parallel with its long-axis direction, the Z-axis was then set across the centers of the long axis of both C5 and C6 vertebral pedicles, and finally, the X-axis should be vertical to both the Y-axis and Z-axis. To obtain the middle surface of the intervertebral foramen, C5/6 may be cut through the Y-Z plane provided by the system (fixed coordinate system ensuring the reproducibility of test). Similarly, we located the internal and external areas according to the inner and outer notch of the pedicle of the vertebral arch. The tunnel between the internal and external areas was considered the intervertebral foramen canal. Canal volume can be calculated directly using the software (Fig. 6a, b). A 0.1-mm-high 3D structure that resembles a cylinder may be achieved by cutting out on the X-axis direction, and two base surfaces of the cylinder were 0.05 mm away from each side of the middle area. According to the calculus principle, the middle area may be obtained by dividing the measured volume of this 3D structure with 0.1 mm. Figure 7 presents the middle area of the intervertebral foramen. Moreover, 0.1 mm of the inner most intervertebral foramen was intercepted to establish another cylinder to calculate the internal area (Fig. 8a, b). The same procedure was applied to the external area (Fig. 9a, b).

The mean middle areas of intervertebral foramens measured by VR, MPR of CT, and MPDM with laser scanner were 77.01 ± 9.18, 81.11 ± 11.25, and 82.83 ± 11.66 mm^2. The comparison results demonstrated a statistically significant difference for VR and MPR ($t = 2.666$, $P = 0.045$) or VR and MPDM ($t = 4.561$, $P = 0.006$); however, there was no significant difference between MPR and MPDM ($t = 2.297$, $P = 0.070$). According to the principle of measurement, the middle areas measured by MPR and MPDM could be considered the same section of the intervertebral foramen. However, the middle area measured by VR may represent a different position from the area measured by MPR and MPDM, leading to the significant differences.

With the increase of the intervertebral distraction and bone graft height, the size of the intervertebral foramen started to decrease after it increased to a certain point (Table 1). When the graft height was 160% of the baseline height, there was a

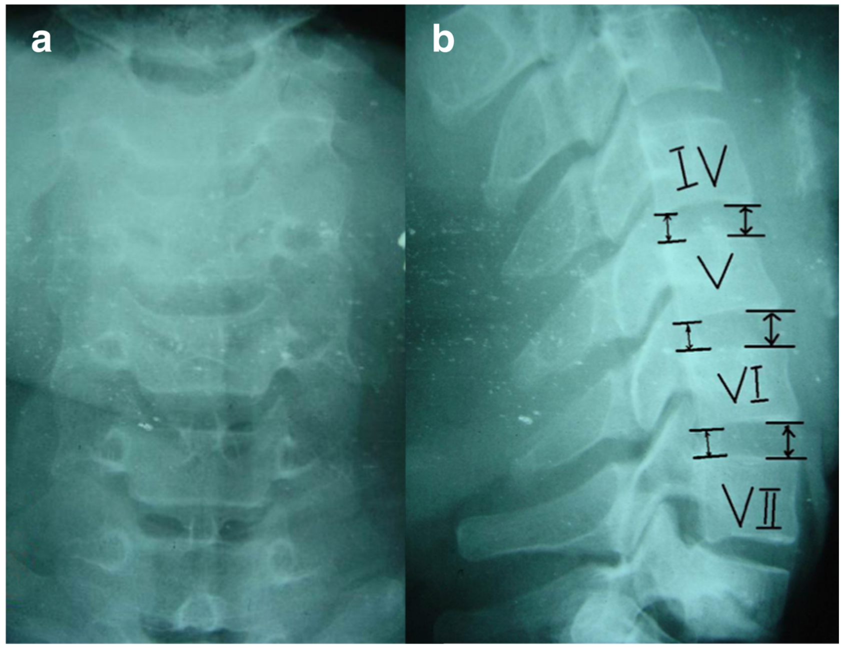

Fig. 2 X-ray for the experimental model. **a** The anteroposterior film. **b** The lateral film. We measured the anterior and posterior heights of each disc space and subsequently calculated the mean height as the disc space height of C4/5, C5/6, and C6/7, separately

significant difference between the volume of the intervertebral foramen ($Pv = 0.049$), the area of its middle region ($Pm = 0.015$), and external opening ($Po = 0.024$), and the corresponding parameters of the intervertebral foramen with the baseline height. These findings indicate that the size of the intervertebral foramen significantly increased when the graft height reached 160% of the baseline height after cervical anterior decompression.

Discussion

Solid reconstitution involves a 3D image constructed with 2D images of an object's surface and body gained from tomography (CT scan or magnetic resonance imaging). To date, the precision of solid reconstitution is related to the number of 2D images obtained per unit length. However, as a result of the limited precision of equipment, errors, such as shift and rotation, are almost inevitable with any method.

The surface-based 3D reconstitution model is constructed with images from 3D laser scanning, which, as a new 3D structural design technology [4], plays an important role in medicine [5–7], particularly oral and maxillofacial surgery. Currently, the laser scanning precision may reach 0.01 mm; therefore, it meets the requirements of simulation and measurement of various human bone structures.

In the present study, there was a significant difference between VR and MPR, which may be caused by the different sections of the intervertebral foramen selected. VR testing requires the measured area parallel to the computer screen, so there was too much influence of subjective factors. MPR could statically test any section of the intervertebral foramen and was relatively objective. Nevertheless, measurement by the CT station requires a manual delineation of the intervertebral foramen with a mouse, which thus leads to poor

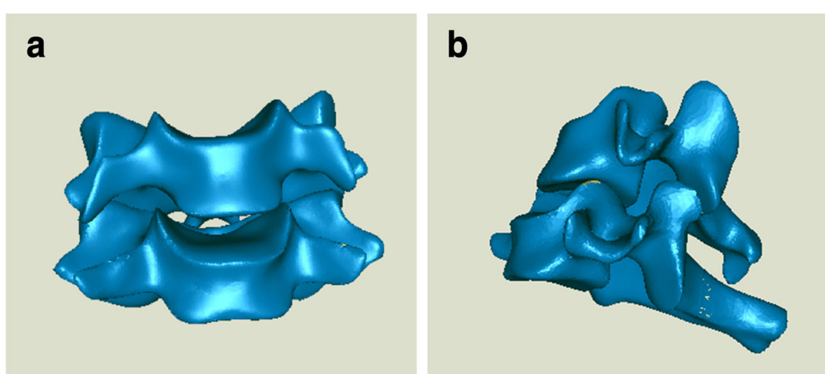

Fig. 3 C5-C6 FSU in baseline height, viewed from the front (**a**) and the side (**b**)

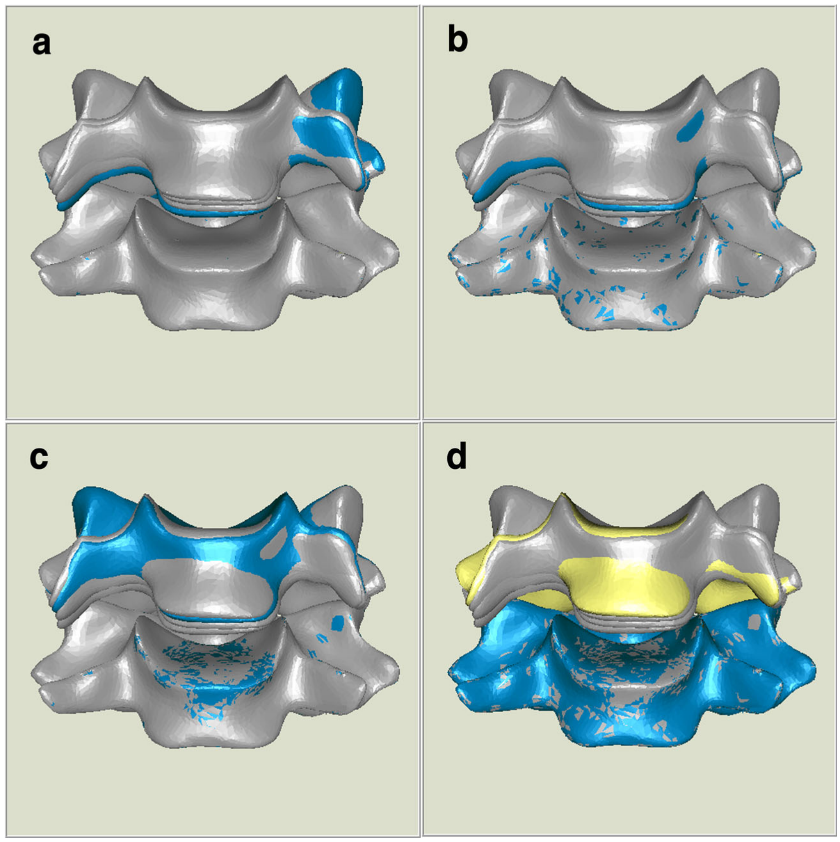

Fig. 4 3D reconstituted images of C5-C6 FSU with four graft sizes. With graft sizes of 100 (**a**), 130 (**b**), and 160% (**c**) of the baseline height; the blue area of upper vertebra represents C6. **d** With graft sizes of 190% of the baseline height; the yellow area represents C6. The front vertebrae body portion of C5-C6 FSU is higher, but the posterior intervertebral foramen portion is lower than the state with 160% of the baseline height

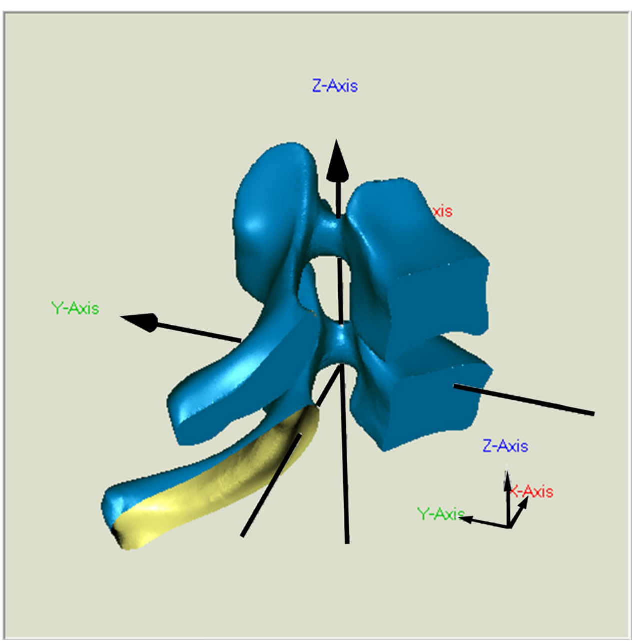

Fig. 5 Establishment of the coordinate system setting. The *Y*-axis crosses the center of the lateral axis of the C6 vertebral pedicle and is parallel with its long-axis direction. The *Z*-axis was then set across the centers of the long axis of both C5 and C6 vertebral pedicles. The *X*-axis should be vertical to both the *Y*-axis and *Z*-axis

measurement repeatability and low precision and requires repeat testing by numerous radiologists. Moreover, it cannot achieve an objective measurement of a fixed section of the same intervertebral foramen when the intervertebral space height is changing.

MPDM have been obtained from practice, and no similar method has been reported to date. This method may successfully avoid the subjective factors in CT measurement and measure a particular section of the intervertebral foramen; thus, it represents an ideal way to measure the intervertebral foramen. The 3D C5-C6 FSU images with excellent likeness reset the coordinate system in software Geomagic8.0, which therefore guarantees the stability and repeatability of the experiment. When the area of the middle region of the intervertebral foramen is measured, the vertebral pedicle center does not change, hence the *Y*-axis and *Z*-axis; therefore, the *Y*-*Z* plane is the median surface, and minor area changes may be detected. Geomagic8.0 can measure only the volume of 3D objects; however, in the present study, according to calculus principle, the area of the middle region of the intervertebral foramen may be obtained by dividing the measured volume of this 3D structure with 0.1 mm so that an area measurement with a precision up to 0.1 mm^2 may be achieved.

Laser scanning can provide images of high fidelity, whereas 3D reconstitution can reproduce the bony surfaces; therefore, this method can guarantee precision of various bone

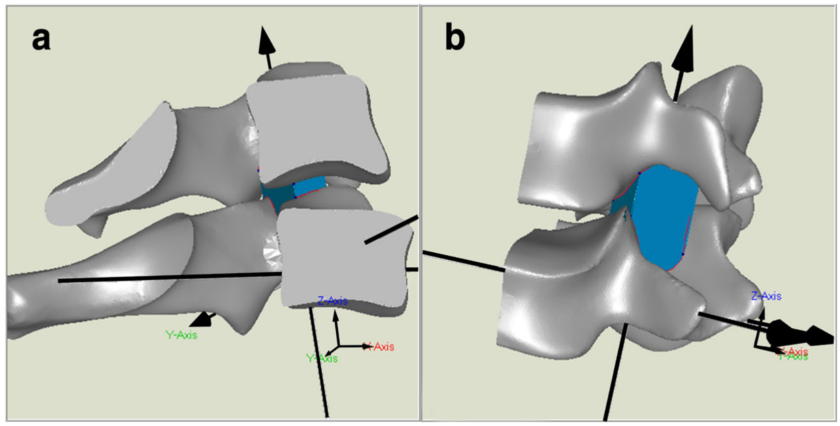

Fig. 6 Measurement of C5/6 intervertebral foramen volume. The tunnel between the inner (**a**) and outer (**b**) pedicle notches of the vertebral arch was considered the intervertebral foramen canal, which is represented by the blue area enclosed by the red line

structure measurements. However, for this method, overall scanning of the bony surfaces is needed to obtain spatial information. Currently, laser scanning reconstitution is predominately performed in laboratories. With its application mainly lying in experimental settings, its clinical application is primarily used for stomatology and plastic, whereas it is less frequently used in clinical orthopedics. Schmidburg et al. [8] measured the spatial capacity of the equine cervical vertebra canal, and Araki et al. [9] investigated the congruency of the articular cartilage surface of the knee between the recipient and donor site during autogenous osteochondral grafting; both groups used 3D laser scanning. Body data measurement, however, remains a necessary component of research; dynamic observation of body data may provide substantial guidance

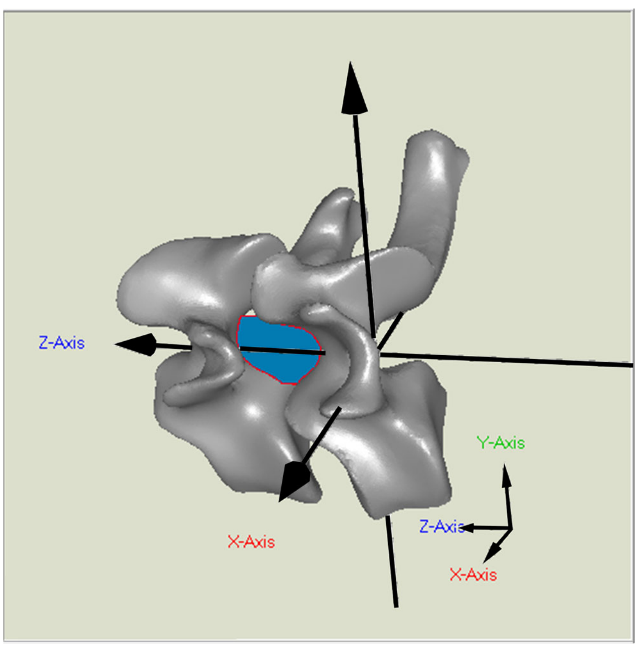

Fig. 7 The middle area of the C5/6 intervertebral foramen. The middle area was located on the *Y-Z* plane where *X* equals the 0 direction and was calculated by measured volume of a 3D structure with 0.1 mm and the calculus principle. The area is represented by the blue area enclosed by the red line

for clinical practice. MPDM are also applicable in live bone data measurement by 3D reconstitution with technologies such as CT. Dynamic measurement through the simulation of various functional states is on our future research agenda.

The intervertebral foramen became smaller following the degeneration of the cervical spine. Intervertebral collapse is the determinant factor [10]. The intervertebral foramen volume is a critical parameter for diagnosing cervical spondylosis of nerve-root-type [11] and is closely related to cervical radicular neuralgia [12]. Lestini and Wiesel [13] reported that more than 97% of cervical spondylosis patients had an X-ray that indicated intervertebral foraminal stenosis. Similarly, Lee et al. [14] reported that more than 82% of cervical spondylosis patients could be diagnosed as intervertebral foraminal stenosis from an X-ray that showed intervertebral collapse. Humphreys et al. [15] compared the degeneration difference between patients with or without cervical spondylosis symptoms, and the results indicated that patients with symptoms have a smaller intervertebral foraminal, including a supra-inferior diameter, anteroposterior diameter, and the overall area.

Opinions differ regarding the appropriate bone graft height. Robinson and Smith [16] suggested the height to be 10–15 mm. White and Panjabi [17] and Panjabl [18] indicated that 4–5 mm were relatively proper. Rothman and Simenone [19] set it at 7 mm. Caspar et al. [20], Clements and O'Leary [21], and Tippets and Apfelbaum [22] all proposed that the optimal distraction height should be between 1 and 2 mm; however, their conclusions were mainly based on experience and lacked empirical evidence. Brower et al. [23] performed a retrospective study of 59 patients who had undergone anterior interbody fusion and determined that a bone graft over 4 mm high showed a tendency of bone union. Olsewski et al. [24] investigated the changes of bearing stress in the graft and facet joint with different graft heights after grafting with a single intervertebral decompression and determined that the bearing stress rates significantly decreased when the distraction height reached 3 mm.

Wang et al. [1] showed that postoperative anterior column height restoration affected the improvement rate; if the

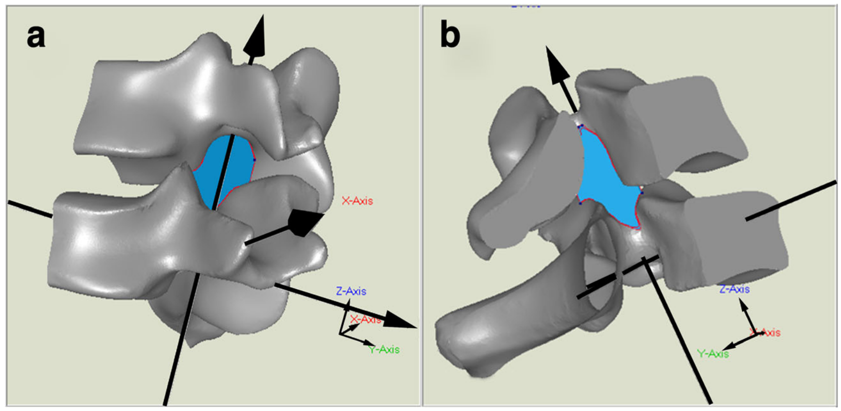

Fig. 8 The internal area of C5/6 intervertebral foramen measured, viewed from the outside (**a**) and the inside (**b**). The inner pedicle notch of the vertebral arch was considered the internal area, which is represented as the blue area enclosed by the red line. Briefly, 0.1 mm of the inner most intervertebral foramen was intercepted to establish another cylinder to calculate the internal area

restored height was < 2 mm, the improvement rate was relatively low. However, if the restored height was > 6 mm, the intervertebral foramen height exceeded the bearing capacity of the surrounding tissues of the operated cervical vertebra segments, which could cause straining of the joint capsule and ligament and, more seriously, over spinal cord stretch that could affect the spinal cord function recovery and thus decrease the postoperative improvement rate of neurological function. Research measurements have demonstrated that when the anterior column height increases by 3.6–10.8%, the increase is linearly associated with the postoperative improvement rate. Therefore, effective restoration of the anterior column height is critical for the improvement of surgical outcomes; however, the restoration should be within a proper range, and blind distraction of the intervertebral space is not acceptable.

In the present study, when the height of the implanted grafts was 190% of the baseline height, the intervertebral foramen decreased (Figs. 4c, d and 10). Over distraction of the intervertebral space may enlarge only the anterior column and not the posterior column results from the limit of tensile stress of the surrounding soft tissues (e.g. little joint capsule, posterior longitudinal ligament and ligamentum flavum). The upper and lower end plates became not parallel, and the entire intervertebral space shrunk.

Cao et al. [25] performed an experiment regarding the stability of movement immediately after the subtotal resection of a single cervical vertebra and bone grafting. In the experiment, after the subtotal resection of intact C5, the space between C4 and C6 was distracted of bone grafts of five heights in sequence, namely, 0, 2, 4, 6, and 8 mm, based on the decompression groove height. Biomechanical tests were conducted under the six states; 3D and 6-DOF (degree of freedom) movements of C4, C5, and C6 were recorded by a spinal 3D movement testing machine; the range of 3D and movement of C4-C5 and C5-C6 segments under different loading conditions were measured by image-processing computer software and a spinal movement analysis application. The results showed that the bone graft was essential for the stability of immediate movement of operated segments after subtotal resection of single cervical vertebra and decompression, whereas the optimal intervertebral distraction height should be 4–6 mm.

A comprehensive evaluation of various factors is necessary for optimal bone graft height selection. This evaluation features an analysis of the tendency of bone union and postoperative improvement rate, stress ratio of the facet joint and biomechanical test, originality, and clinical experience. Although opinions and standards may differ, evaluations may represent a helpful clinical reference. The restoration of the original

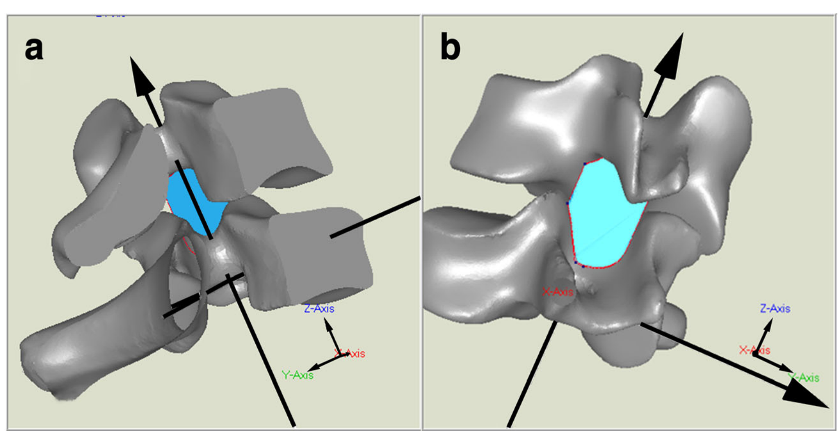

Fig. 9 The external area of C5/6 intervertebral foramen measured, viewed from the inside (**a**) and the outside (**b**). The outer pedicle notch of the vertebral arch was considered the external area, which is represented as the blue area enclosed by the red line. Briefly, 0.1 mm of the outer most intervertebral foramen was intercepted to establish another cylinder to calculate the external area

Table 1 Changes in the intervertebral foramen size with different bone graft heights under decompression of a single segment of lower cervical vertebrae (shown with % recovery from the baseline)

Bone graft height (mm)	Volume (%)	Middle area (%)	Internal area (%)	External area(%)
6.99 (130% of baseline)	107.2 ± 1.3	108.1 ± 2.3	103.5 ± 1.2	107.8 ± 6.7
8.61 (160% of baseline)	118.2 ± 5.8	120.7 ± 6.4	116.9 ± 8.1	116.8 ± 13.2
10.22 (190% of baseline)	106.1 ± 5.3	106.2 ± 5.3	100.7 ± 4.3	105.1 ± 7.8

intervertebral foramen size, removal of compression on nerve roots, and alleviation of radicular symptoms are among the important purposes of interbody distraction and bone graft fusion with cervical anterior decompression. The intervertebral foramen size is correlated with the intervertebral height; consequently, the intervertebral foramen size becomes an important indicator for the bone graft height.

Relevant studies have been conducted. An et al. [26] performed cervical discectomy and decompression with six fresh adult cervical spine specimens and used ilium of different heights for intervertebral distraction. The height and area of the intervertebral foramens exhibited a significant increase with 2–3 mm distraction, whereas distraction greater than 3 mm did not significantly increase the area of the intervertebral foramen. Bayley et al. [27] measured the intervertebral foramina with different bone graft heights and proposed that the optimal bone graft height should be 5 mm. They

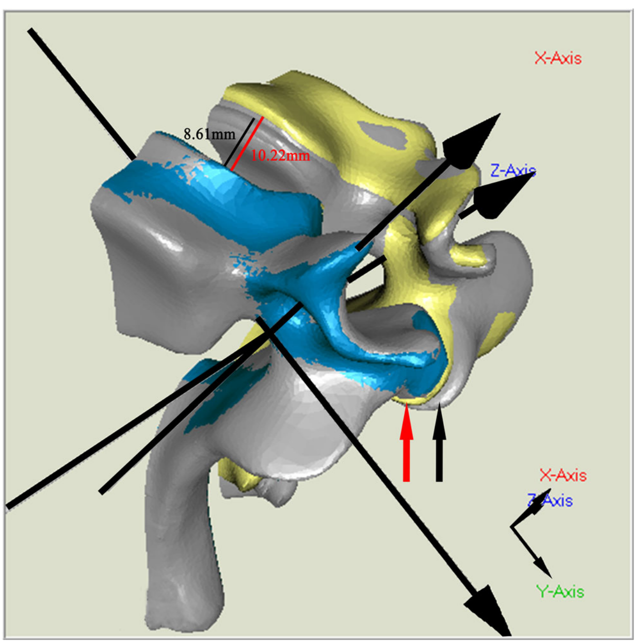

Fig. 10 When the height of the implanted grafts was 190% of the baseline height, the intervertebral foramen decreased. The yellow area and red arrow indicate the implanted state with 190% of the baseline height at 10.22 mm. The lower gray area and black arrow indicate the implanted state with 160% of the baseline height at 8.61 mm. Although the 190% implanted graft was higher than 160% implanted graft in the anterior portion, the former was lower than the latter in the posterior portion, resulting from the limit of tensile stress of the surrounding soft tissues

emphasized that restoration of the lost disc height is the safest and most important means of correcting foramina stenosis and relieving fifth lumbar root compression. However, both of the previously described studies adopted absolute values of the graft height while neglecting the preoperative intervertebral space height, and the measurement methods were outdated; thus, they failed to sensitively reflect the changes of the intervertebral foramen.

The present study, based on clinical practice, incorporated the individual differences in the intervertebral height and the concept of baseline height. The results indicated that the size of the intervertebral foramen significantly increased with the graft height at 160% of the baseline height after cervical anterior decompression; under this state, intervertebral foraminal and canal stenosis could be effectively alleviated to maintain a relatively friendly intervertebral foraminal environment.

It was concluded that a 3D laser scanner can produce high-fidelity 3D surface images by scanning bone structures and may be used to measure various anatomical parameters of the skeletal system; the new MPDM, which measure the cervical intervertebral foramen, feature objectivity and precision, as well as the avoidance of the objective factors in CT measurement and excellent dynamic measurement of a particular plane of the intervertebral foramen; thus, it is an ideal method to measure the intervertebral foramen. The foramen volume displayed a significant increase when the graft height was 160% of the mean normal intervertebral space heights. However, with the increase of the bone graft height, the size of the intervertebral foramen began to decrease after increasing to a certain degree.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The procedure was approved by the Institutional Human Investigation Committee of Sun Yat-sen Memorial Hospital, Sun Yat-sen University, Guangzhou, China.

Statement of informed consent This study was performed on cadaver specimens; thus, "Informed Consent" was not applicable.

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