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Biomechanical Effect of Different Graft Heights on Adjacent Segment and Graft Segment Following C4/C5 Anterior Cervical Discectomy and Fusion: A Finite Element Analysis

Authors' Contribution:

Study Design A
Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
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Background:

The finite element analysis (FEA) was used to explore the effect of different graft heights on adjacent segment and graft segment stress after C4/5 anterior cervical discectomy and fusion (ACDF).

Material/Methods:

A detailed, geometrically accurate 3-dimensional cervical spine model was successfully built from computed tomography (CT) scanning of a healthy adult male. We changed the graft height in C4–C5 to be 90%, 150%, 175%, and 200% of the preoperative disc height and simulated the postoperative scenarios with different bone graft height, respectively. A stress analysis was conducted on the adjacent segment and graft segment.

Results:

The maximum von Mises stress on C3–C4 showed that when the graft height was 200%, the values were 0.99 MPa, 0.85 MPa, 0.91 MPa, and 0.89 MPa in different loading conditions. For C5–C6, the maximum von Mises stress was 0.77 MPa, 0.83 MPa, 0.91 MPa, and 0.81 MPa, observed when the graft height was 175%, except in extension condition. With regard to graft segment (C4–C5), the biggest von Mises stress was 1.25 MPa, 1.77 MPa, 1.75 MPa, and 1.81 MPa observed at 200% graft height. For these 3 segments, the smallest von Mises stress was found at 150% graft height under the 4 loading conditions.

Conclusions:

The graft height makes an important difference on the stress on the adjacent segment and the graft segment after anterior cervical discectomy and fusion. A 150% graft height was considered the proper graft height in C4/C5 ACDF, with the lowest stress on the adjacent segment and the graft segment.

MeSH Keywords:

Biomechanical Phenomena • Finite Element Analysis • Intervertebral Disc • Spinal Fusion

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Background

Anterior cervical discectomy and fusion (ACDF) is widely performed for the treatment of cervical degenerative disc disease [1]. It can allow direct remove of anterior pressure and usually is accompanied with interbody fusion and anterior fixation. However, ACDF has been associated with the development of new degeneration at levels adjacent to the fused segments [2,3].

The degeneration adjacent to the level of spine arthrodesis is called adjacent segment degeneration (ASD). Risk factors for the ASD have been proposed in the literature, including graft height [4], graft type [5], fusion plate placement [6], and post-operative cervical alignment [7]. In addition, increased stress on the adjacent segment may lead to overload and instability in the segment, eventually resulting in ASD [2,8,9].

A biomechanical study using finite element analysis (FEA) can help to elucidate the complex biomechanical properties of the spine, including stresses, strains, and loads under different conditions. Although stress on the adjacent segment after ACDF has been reported in many studies [10-13], the stress changes based on different graft height has not been studied. Hence, the objective of the present study was to analyze the effect of different graft heights on the stress on the adjacent segment and the graft segment after ACDF by FEA.

Material and Methods

Finite element (FE) modeling

The computed tomography (CT) images of a cervical spine were obtained at 1-mm intervals from a healthy male volunteer (age 36 years, weight 75 kg, and height 175 cm) who had not suffered any cervical disease. The images were imported into MIMICS 12.1 (Materialise, Leuven, Belgium) to make segmentation and obtain the bone boundaries. The geometry was processed using Geomagic Studio 10.0 (Geomagic, Research Triangle Park, NC, USA) to smooth the uneven surface. Then, the model was imported into the Hypermesh 11.0 (Altair Engineering, Troy, MI, USA) to build the numerical model. Finally, the FE was imported into ANSYS 15.0 (ANSYS, Canonsburg, PA, USA) to process static solution.

The intact FE model is shown in Figure 1. The model consisted of 4 vertebrae (C3, C4, C5, and C6), 3 intervertebral discs (C3–C4, C4–C5, and C5–C6), including cortical bone, cancellous bone, intervertebral discs, ligaments, and all other important parts. Solid elements were used in the modeling of the vertebral bodies and the posterior elements, but the material was described as isotropic. Shell elements were used for

cortical bone and solid tetrahedral elements were used for cancellous bone. Meanwhile, cortical endplates and cortical shells were set as 1-mm thick and connected with solid cancellous elements by sharing the same node. The aforementioned materials were assumed to be homogeneous isotropic linear elastomers.

The material properties are listed in Table 1 [14]. Four different ligaments approximating the ligamentous structures in the cervical spine were incorporated into the FE model as tension-only nonlinear springs: anterior longitudinal ligaments (ALL), posterior longitudinal ligaments (PLL), interspinous ligaments (ISL), and ligamentum flavum (LF). Tensile force-deflection properties of cervical spine ligaments were previously described [15]. The final intact FE model consisted of 473 186 solid elements and 122 540 shell elements.

Validation of model

Three-dimensional surface contact elements were used for the contact and sliding effect between the articular facets. Statistical analysis was performed by applying 1.0 Nm of flexion, extension, axial rotation, and lateral bending moments with 73.6 N of axial compression superior to C3. The boundary condition was simulated by fixing the inferior surface of the C6 vertebra under constraint of different degrees of freedom. The validity of the FE model was verified by comparing the predicted data with the results reported in the literature [16].

Surgery simulation

During the actual operation, the “interjob” support is used to support the vertebral space after removing the anterior longitudinal ligament, removing the lesion disc, and removing the corresponding upper and lower endplates. Then the corresponding size of the autologous bone mass is taken. The implant is inserted into the intervertebral space. All models were based on a validated model of the aforementioned intact C3–C6 model.

The height of anterior intervertebral space was 4.4 mm preoperatively. Four FE models were built with heights of 4.0 mm, 6.6 mm, 7.7 mm, and 8.8 mm, respectively at 90%, 150%, 175%, and 200% of the height between C4–C5 preoperative disc height. The height was changed by translating the elements and geometry in Hypermesh 11.0.

We turned the property of the disc annulus and disc nucleus into cancellous bone at C4–C5 [17]. The ALL were excised to simulate the surgery as closely as possible. The same boundary and loading conditions were applied to the 4 models. In all simulations, 73.6 N of compressive preload was applied to the C3 upper endplate. In addition, a pure moment of 1.0

Figure 1. The finite element (FE) model. **(A)** Soft tissues include disc annulus, nucleus pulposus, and anterior longitudinal ligaments (AAL), posterior longitudinal ligament (PLL), ligamentum flavum LF, and interspinous ligament (ISL). **(B)** Endplate and hard tissues include cancellous, cortical, and posterior elements. **(C)** The schematic diagram of load and boundary: C6 inferior endplate was fixed and pure torque of 1.0 Nm and compressive load of 73.6 N were applied on the reference point at upper endplate of C3. **(D)** FE model after anterior cervical discectomy and fusion (ACDF) surgery.

Table 1. The material properties of the spine soft tissues and hard tissues used in the finite element model.

Tissues	Young's modulus (MPa)	Poisson's ratio	Elements type
Cortical bone	10 000	0.29	Shell63 (1 mm)
Cancellous bone	100	0.29	Solid185
Posterior element	3500	0.29	Solid185
Disc annulus	3.4	0.4	Solid185
Disc nucleus	3.4	0.49	Solid185
Endplate	500	0.4	Shell63 (1 mm)
Titanium plate	120 000	0.3	Solid185
Titanium screw	120 000	0.3	Solid185

MPa – megapascal.

Nm in different directions (flexion, extension, axial rotation, and lateral bending) was applied on the C3 endplate for the 4 simulations.

In this case, a C4–C5 anterior titanium alloy plate (height 27.5 mm) and 4.0×13.0 mm self-tapping screws (Medtronic Sofamor Danek, Memphis, TN, USA) were simulated. The upper screws were inserted in the middle of the anterior vertebral wall and parallel with the upper vertebral endplate, and the lower screws were inserted parallel with the horizontal line. In SolidWorks 12.0 (SolidWorks, MA, USA), the titanium plate and vertebral bodies were fixed with the screws and the connection parts of the titanium plate, the screws and the vertebral bodies were simulated with the contact method of binding. The bone graft was assumed bound to the adjacent vertebral body completely.

Results

Validation

The comparison between *in vitro* data and predicted value in the FE model are shown in Table 2. All the predicted responses were consistent with the results of *in vitro* experiments reported in the literature [16].

Stress distribution

The von Mises stress on each disc are shown as Table 3. The values are in order of flexion, extension, axial rotation, and lateral bending.

For upper adjacent segment (C3–C4), under different heights of the bone graft, the maximum von Mises stress on C3–C4 showed when the height of bone graft was 200%. The values

Table 2. ROM of every segment under different conditions.

Load scheme	Experiment data			Current model		
	C3–C4	C4–C5	C5–C6	C3–C4	C4–C5	C5–C6
Flexion	3.4±2.1	4.8±1.9	4.4±2.8	4.3	5.8	6.8
Extension	4.3±2.9	5.3±3.0	5.5±2.6	5.6	6.8	6.8
Rotate	5.1±1.2	6.8±1.3	5.0±1.0	5.3	6.3	5.5
Lateral bending	9.0±1.9	9.3±1.7	6.5±1.5	7.8	9.6	5.2

ROM – range of motion.

Table 3. The maximum von Mises stress on discs under different condition with different bone graft height.

Maximum von Mises stress (MPa)	C3–C4				C4–C5				C5–C6			
	90%	150%	175%	200%	90%	150%	175%	200%	90%	150%	175%	200%
Flexion	0.88	0.86	0.89	0.99	1.09	0.65	1.23	1.25	0.68	0.60	0.77	0.74
Extension	0.72	0.68	0.78	0.85	1.46	1.17	1.56	1.77	0.80	0.71	0.75	0.83
Rotate	0.82	0.74	0.87	0.91	1.60	1.10	1.54	1.75	0.85	0.69	0.91	0.82
Lateral bending	0.76	0.65	0.81	0.89	1.35	1.14	1.72	1.81	0.79	0.75	0.81	0.71

MPa – megapascal.

Figure 2. The von Mises stress distributions on C3–C4 with different graft heights.

Figure 3. The von Mises stress distributions on C5–C6 with different graft heights.

Figure 4. The von Mises stress distributions on C4–C5 with different graft heights.

were 0.99 MPa, 0.85 MPa, 0.91 MPa, and 0.89 MPa in different loading conditions. The values at 150% of graft height were only 87%, 80%, 81%, and 73% of the values at 200%.

For lower adjacent segment (C5–C6), the maximum von Mises stress values were 0.77 MPa, 0.83 MPa, 0.91 MPa, and 0.81 MPa, observed with the height of bone graft at 175%, except extension condition. The values at 150% of graft height were only 78%, 86%, 76%, and 93% of the biggest values.

With regard to graft segment (C4–C5), the biggest von Mises stress values were 1.25 MPa, 1.77 MPa, 1.75 MPa, and 1.81 MPa, observed when the height of bone graft was 200% of preoperative disc height. The values were smallest at 150% of the graft height. The smallest values were 52%, 66%, 63%, and 63% of the biggest values.

The stress cloud diagram is shown in Figures 2–4. It can be seen that the graft height had little effect on adjacent segment stress distribution. Maximum value appeared in front of the disc annulus during flexion. “U” shape was observed with the bigger stress on the annulus disc back compared to the other three sides under extension. The stress was mainly concentrated on both sides of the vertebral body, the joint of vertebral arch and disc under bending and rotation.

Discussion

ACDF is considered the gold standard for the treatment of degenerative cervical diseases. Previous studies have reported that patients can achieve significant neurologic recovery and alleviation of pain after ACDF [18]. Distraction of disc space is routinely performed in ACDF, which could contribute to visualized decompression, cage insertion, and disc height recovery.

Opinions regarding graft height in ACDF are still controversial. In 1958, Smith and Robinson proposed that the intervertebral space should be 10–15 mm [19]. While in 1988, White et al. thought that 4–5 mm high bone graft was appropriate [20]. Kawakami et al. concluded that 2–5 mm distraction was a proper distraction height, resulting in lower rate of axial neck pain [21]. Olsewski et al. investigated the stress changes in the graft and facet joint in the condition of different graft heights in ACDF and concluded that the bearing stress rates significantly decreased when the distraction height was in excess of 3 mm [22].

Being increasingly utilized by orthopedic researchers, FEA is a mathematical model that helps to elucidate the complex biomechanical properties of the spine, including stresses, strains, and loads under differing conditions. A few studies have analyzed the stress distribution after ACDF by FEA. But the stress on adjacent segments and graft segments under the condition

of different graft heights after ACDF has not been studied. In our study, we found that 150% distraction lead to less stress on adjacent segments following ACDF. Recently, in a cadaveric study, Yang et al. concluded that 160% of the mean height of adjacent intervertebral spaces was the optimal graft height from the point of foramen size [23]. Our result was similar to their opinion.

The association between disc pressure and disc degeneration has been studied. The intervertebral disc lacks blood supply. It depends primarily on the diffusion of nutrients from the peripheral blood vessels and vertebral endplates through the extracellular matrix [24]. Increased disc pressure tends to alter the diffusion properties of nutrients delivered from the surrounding blood supply, leading to waste accumulation. Failure to adequately remove waste from intervertebral discs leads to lactic acid accumulation and a decrease in pH, which disrupts metabolism and leads to cell death [25].

Besides, we found that 150% of graft height lead to a smaller stress on the graft segment. The optimal force needed for bone graft is unknown. Appropriate stress may enhance the rate of fusion. However, excessive stress on the bone graft and end plates may result in fusion failure because of graft dislodgement and end plate fracture [26]. Although for stress it is not that smaller is better, and this study finding may contribute to further studies that explore the proper stress on the bone graft in ACDF.

Our study had some limitations. FEA was extremely versatile and powerful, but incomplete knowledge regarding mechanical behaviors was challenging [27]. Besides, the graft height in ACDF has been associated with the preoperative intervertebral space. Only 1 case was analyzed in our study, so there should be more cases reviewed to support our conclusion. In this study, the mechanical effects of muscles were not taken into consideration. In addition, different insertion methods for screws may influence the results. However, the present study provides a foundation for further *in vivo* investigations to further assess our findings. There are so many controversies and unanswered questions on this topic. Thus, we believed this would be an interesting topic to explore. Further research is needed to investigate the appropriate graft height on the adjacent segment and the graft segment. We hope that this paper will help surgeons better understand the stress forces that occur in the cervical spine after ACDF, especially when there is some degree of degeneration in the adjacent segment.

Conclusions

The graft height can make an important difference on the stress on adjacent segments and graft segments after anterior cervical

discectomy and fusion. A 150% graft height was a proper graft height in C4/5 ACDF, with lowest stress on the adjacent segment and the graft segment.

References:

1. Cloward RB: The anterior approach for removal of ruptured cervical disks. *J Neurosurg*, 1958; 15: 602–17
2. Baba H, Furusawa N, Imura S et al: Late radiographic findings after anterior cervical fusion for spondylotic myeloradiculopathy. *Spine*, 1993; 18: 2167–73
3. Wu W, Thuomas KA, Hedlund R et al: Degenerative changes following anterior cervical discectomy and fusion evaluated by fast spin-echo MR imaging. *Acta Radiologica (Stockholm, Sweden)*, 1987; 1996; 37: 614–17
4. Li J, Li Y, Kong F et al: Adjacent segment degeneration after single-level anterior cervical decompression and fusion: Disc space distraction and its impact on clinical outcomes. *J Clin Neurosci*, 2015; 22: 566–69
5. Samartzis D, Shen FH, Goldberg EJ, An HS: Is autograft the gold standard in achieving radiographic fusion in one-level anterior cervical discectomy and fusion with rigid anterior plate fixation? *Spine*, 2005; 30: 1756–61
6. Lee DH, Lee JS, Yi JS et al: Anterior cervical plating technique to prevent adjacent-level ossification development. *Spine J*, 2013; 13: 823–29
7. Katsuura A, Hukuda S, Saruhashi Y, Mori K: Kyphotic malalignment after anterior cervical fusion is one of the factors promoting the degenerative process in adjacent intervertebral levels. *Eur Spine J*, 2001; 10: 320–24
8. Fielding JW: Normal and selected abnormal motion of the cervical spine from the second cervical vertebra to the seventh cervical vertebra based on cinerentgenography. *J Bone Joint Surg Am*, 1964; 46: 1779–81
9. Schwab JS, Diangelo DJ, Foley KT: Motion compensation associated with single-level cervical fusion: Where does the lost motion go? *Spine*, 2006; 31: 2439–48
10. Ren J, Li R, Zhu K et al: Biomechanical comparison of percutaneous posterior endoscopic cervical discectomy and anterior cervical decompression and fusion on the treatment of cervical spondylotic radiculopathy. *J Orthop Surg Res*, 2019; 14: 71
11. Tchako A, Sadegh AM: Stress changes in intervertebral discs of the cervical spine due to partial discectomies and fusion. *J Biomech Eng*, 2009; 131: 051013
12. Fernandes PC, Fernandes PR, Folgado JO, Levy Melancia J: Biomechanical analysis of the anterior cervical fusion. *Comput Methods Biomech Biomed Engin*, 2012; 15(12): 1337–46
13. Li Y, Lewis G: Influence of surgical treatment for disc degeneration disease at C5–C6 on changes in some biomechanical parameters of the cervical spine. *Med Eng Phys*, 2010; 32: 595–603
14. Yoganandan N, Kumaresan SC, Voo L et al: Finite element modeling of the C4–C6 cervical spine unit. *Med Eng Phys*, 1996; 18: 569–74
15. Yoganandan N, Kumaresan S, Pintar FA: Biomechanics of the cervical spine Part 2. Cervical spine soft tissue responses and biomechanical modeling. *Clin Biomech (Bristol, Avon)*, 2001; 16: 1–27
16. Panjabi MM, Crisco JJ, Vasavada A et al: Mechanical properties of the human cervical spine as shown by three-dimensional load-displacement curves. *Spine*, 2001; 26: 2692–700
17. Duan Y, Zhang H, Min SX et al: Posterior cervical fixation following laminectomy: A stress analysis of three techniques. *Eur Spine J*, 2011; 20: 1552–59
18. Garvey TA, Eismont FJ: Diagnosis and treatment of cervical radiculopathy and myelopathy. *Orthopaed Rev*, 1991; 20: 595–603
19. Smith GW, Robinson RA: The treatment of certain cervical-spine disorders by anterior removal of the intervertebral disc and interbody fusion. *J Bone Joint Surg Am*, 1958; 40-a: 607–24
20. White AA, Panjabi MM: Biomechanical considerations in the surgical management of cervical spondylotic myelopathy. *Spine*, 1988; 13: 856–60
21. Kawakami M, Tamaki T, Yoshida M et al: Axial symptoms and cervical alignments after cervical anterior spinal fusion for patients with cervical myelopathy. *J Spinal Disord*, 1999; 12: 50–56
22. Olsewski JM, Garvey TA, Schendel MJ: Biomechanical analysis of facet and graft loading in a Smith-Robinson type cervical spine model. *Spine*, 1994; 19: 2540–44
23. Yang R, Ma M, Huang L et al: Influences of different lower cervical bone graft heights on the size of the intervertebral foramen: Multiple planar dynamic measurements with laser scanning. *Lasers Med Sci*, 2018; 33: 627–35
24. Urban JP, Holm S, Maroudas A, Nachemson A: Nutrition of the intervertebral disc: Effect of fluid flow on solute transport. *Clin Orthop Relat Res*, 1982; (170): 296–302
25. Buckwalter JA: Aging and degeneration of the human intervertebral disc. *Spine*, 1995; 20: 1307–14
26. Hussain M, Natarajan RN, Fayyazi AH et al: Screw angulation affects bone-screw stresses and bone graft load sharing in anterior cervical corpectomy fusion with a rigid screw-plate construct: A finite element model study. *Spine J*, 2009; 9: 1016–23
27. Ryu R, Techy F, Varadarajan R, Amirouche F: Effect of interbody fusion on the remaining discs of the lumbar spine in subjects with disc degeneration. *Orthop Surg*, 2016; 8: 27–33

Conflict of interest

None.