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Cervical Lift-up Basket Laminoplasty after Resection of Spinal Intramedullary Tumors: A Finite Element Analysis and Clinical Image Evaluation

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Abstract

Although reconstructive laminoplasty is commonly performed after resection of spinal intramedullary tumors of the cervical spine, its biomechanical rigidity of laminoplasty framework remains unclear. The objective of this study was to examine the structural reliability of our unique method of cervical lift-up basket laminoplasty by using computed tomography (CT)-based finite element analysis (FEA) and clinical radiological evaluation. A finite element model of cervical laminoplasty was created based on CT images using FEA software. Cervical lift-up basket laminoplasty (Basket) was compared with the standard style of open-door basket laminoplasty (Open-door). Clinical subjects for radiological evaluation comprised 33 patients who underwent cervical lift-up basket laminoplasty after resection of spinal intramedullary tumors. An FEA-equivalent stress histogram showed that stress was moderately dispersed around the basket. Virtual displacement of the spinous process of the Basket model was equivalent to that of the Open-door model in any direction of posterior-to-anterior, right-to-left, or top-to-bottom force. In the clinical analysis, radiological data with a minimum postoperative period of 6 months were obtained in a total of 28 out of 33 patients. No patients underwent revision surgery because of implant-related complications. No significant differences in C2-C7 angle or cervical tilt angle were observed between pre- and postoperatively. The structural rigidity of cervical lift-up basket laminoplasty was equivalent to the open-door style on the FEA. Clinical radiological evaluation suggested that there were no serious adverse events associated with cervical laminoplasty, although the longer postoperative follow-up is mandatory.

Keywords: basket plate, cervical laminoplasty, finite element analysis, spinal intramedullary tumors, ependymoma

Introduction

Reconstructive laminoplasty is commonly performed after resection of spinal intradural tumors of the cervical spine.[1-9] However, cervical laminoplasty may be technically demanding after wide laminectomy for the resection of spinal intramedullary tumors of the cervical spine, and laminectomy alone may cause kyphotic malalignment of the cervical spine long after surgery.[3-5,7,8] Cervical lift-up laminoplasty may become one of the surgical solutions to these drawbacks.[1,2,6,9] The resected laminae can be secured to the original position using titanium plates. A titanium spacer for cervical lift-up laminoplasty (Laminoplasty Basket; AMMTEC Co., Tokyo, Japan) has recently become available.[10,11] Cervical lift-up basket laminoplasty has been applied for the reconstruction of cervical laminae after the resection of spinal intramedullary tumors of the cervical spine in our institute (Fig. 1A).[9] The objective of this study is to examine the structural reliability of our unique method of cervical lift-up basket laminoplasty by using computed tomography (CT)-based finite element analysis (FEA) and clinical radiological evaluation.

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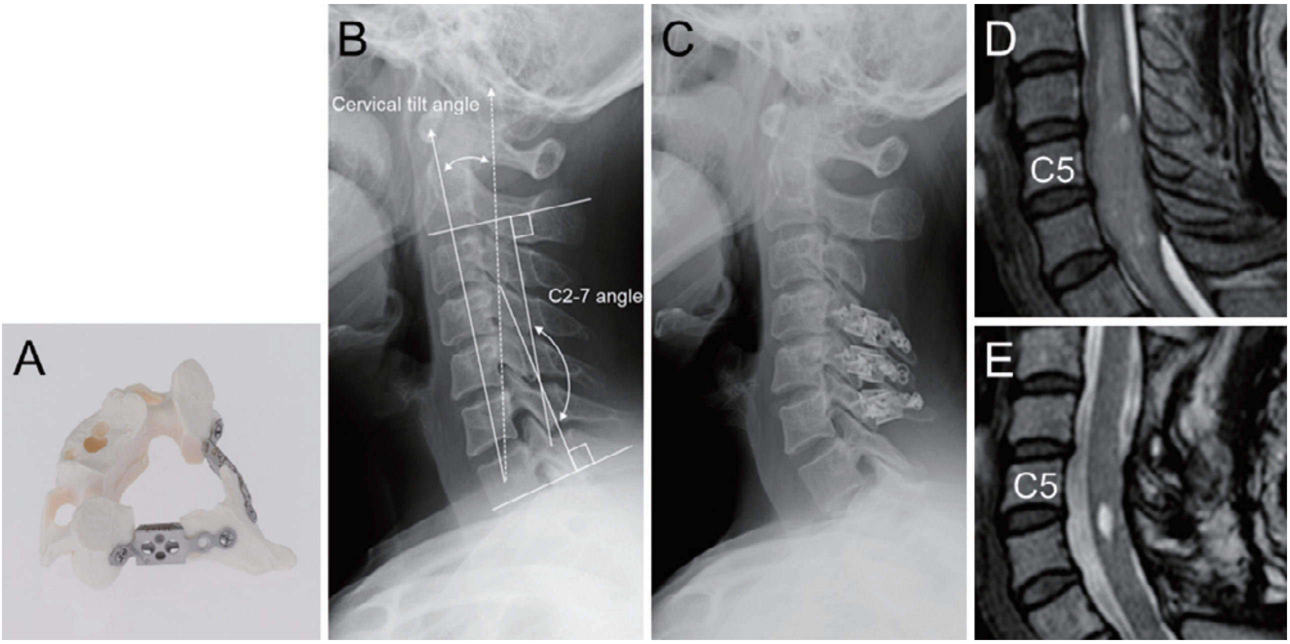

Fig. 1 A case of spinal intramedullary ependymoma. (A) Photograph showing a plastic model of cervical lift-up basket laminoplasty. (B, C) Plain lateral radiographs before (B) and after surgery (C). (D, E) T2-weighted magnetic resonance images before (D) and after surgery (E).

Materials and Methods

Three-dimensional FEA

A finite element model of the intact cervical spine was created based on images from CT using FEA software (Mechanical Finder; Research Center for Computational Mechanics, Tokyo, Japan).[12-14] Preoperative CT images of a patient who underwent surgical resection of a spinal intramedullary ependymoma (female; age, 44 years; height, 163 cm; weight, 63 kg) were used for this analysis (Fig. 1B-E). In the present study, the FEA model for cervical lift-up basket laminoplasty was compared to that of open-door laminoplasty that is widely used. Two types of cervical laminoplasty were created: open-door style with titanium basket (Open-door) and lift-up style with titanium basket (Basket) (Fig. 2A, B). For the Open-door type, a 3.0-mm-wide gutter was made on the left side, and a unicortical hinge leaving 0.4 mm of the cortical bone was made on the right side. The laminar arch of the gutter was reconstructed using titanium monocoque plate spacers (Laminoplasty Basket; AMMTEC Co.). For the Basket type, a 3.0-mm-wide gutter was made on both sides, and the laminar gutters were again reconstructed using titanium monocoque plate spacers. For these two types using basket plates, the basket was filled with hydroxyapatite/collagen composite material (ReFit; HOYA Technosurgical Co., Tokyo, Japan) to promote bone fusion. The material properties and contact setting of the bone and titanium materials used for this CT-based FEA were set with reference to known data (Table 1). The elastic modulus of the bone was assumed based on the conversion formula of Keyak et al.[15] Load conditions under full constraint of the upper and lower endplates of the vertebral body were applied in posterior-to-anterior (PA) direction, right-to-left (RL) direction, and top-to-bottom (TB) direction at the base of the spinous process. Loading force was set to 6 N (a load of 6 N is equivalent to a force of 0.612 kgf) each.

Clinical subjects

During the 5-year period from October 2014 to November 2019, a total of 33 patients underwent cervical lift-up basket laminoplasty for the resection of spinal intramedullary tumors of the cervical spine. Recurrent cases were excluded from study entry. Radiological data with a minimum postoperative period of 6 months were obtained in 28 out of 33 patients. The final participants for clinical radiological analysis were 15 males and 13 females, with a mean age of 46.2 (range, 13-76) years. The mean duration of postoperative follow-up was 31.9 (range, 9-70) months. The mean number of reconstructed laminae was 2.5. Implant-related complications after surgery were divided into four grades based on the postoperative cervical plain radiographs or CT: Grade 0, no apparent implant-related complications; Grade 1, minor complications defined as cases where some screws (but no plates) may be loose, but constructed laminae appear stable on imaging; Grade 2, moderate complications defined as cases where some screws and plates are clearly loose, but constructed laminae still appear stable on imaging; and Grade 3, serious complications defined as cases where some screws and

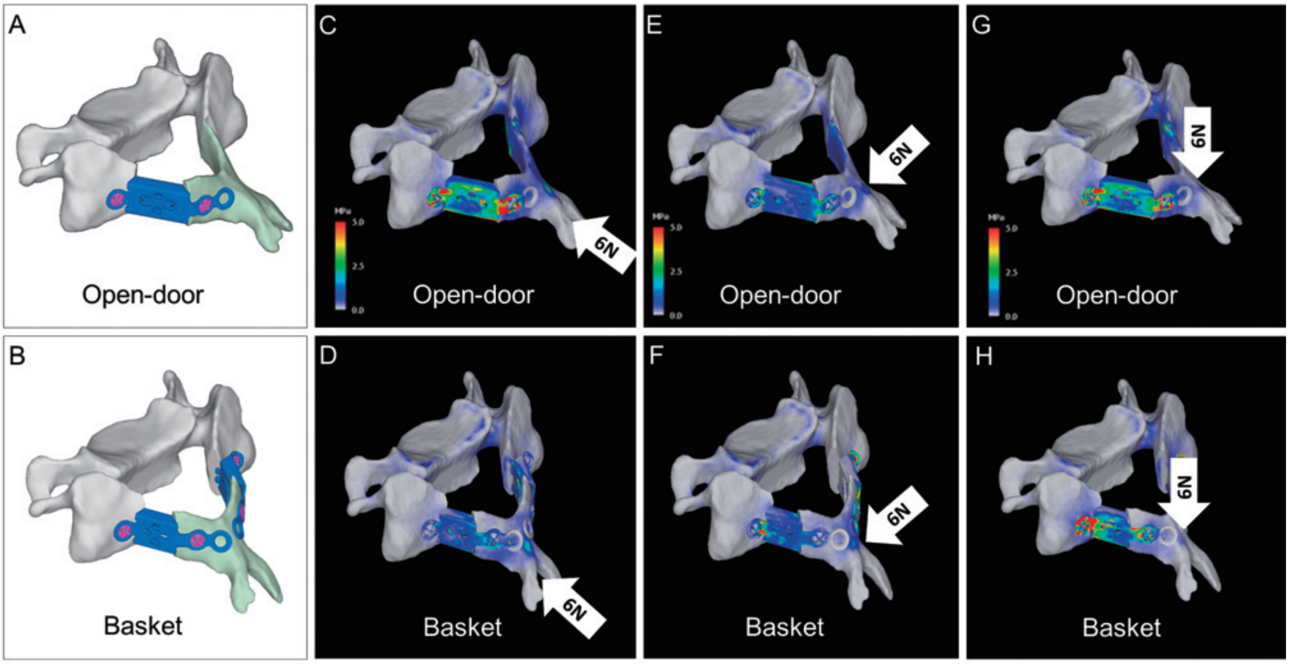

Fig. 2 (A, B) Three-dimensional finite element models. (A) Open-door laminoplasty with titanium basket plate (Open-door). (B) Lift-up laminoplasty with titanium basket plate (Basket). (C–H) The distribution of equivalent stress in each model under three-directional compression conditions of posterior-to-anterior (C, D), right-to-left (E, F), and top-to-bottom (G, H). Corresponding peak stresses were more observed in the titanium basket plate in the Open-door model under posterior-to-anterior compression, more observed in the titanium basket plate in the Basket model under the right-to-left compression, and similar between the two models under the top-to-bottom compression. Please note the direction of compression force (6 N) (arrow).

Table 1 Material properties and contact setting used in the CT-based FE analysis

Material properties Structure	Young's modulus	Poisson's ratio
Bone	Keyak*1, *2	0.4
Titanium basket	106 GPa	0.34
Titanium screw	113 GPa	0.315

Contact setting Structure	Boundary	Friction coefficient
Bone–titanium basket	Contact	0.5
Bone–titanium screw	Contact	0.5
Titanium basket–titanium screw	Contact	0.55

*1: The elastic modulus of the bone was assumed to be based on the conversion formula of Keyak et al.
*2: The laminar arch at the hinge part of the HA model was considered to be plastic, and its Young's modulus was calculated as a value multiplied by 0.05.

plates are clearly loose, and constructed laminae appear unstable on images. The condition of "loose" was defined as a condition in which the screw itself was detached partially or accompanied by a clear zone around the screw. Radiological evaluations before and after surgery included both the C2-C7 angle of spinal curvature and cervical tilt angle (Fig. 1B). A positive cervical tilt angle was defined as the midpoint of the anterior tubercle of C1 being anterior to the vertical line from the midpoint of the C7 vertebral body. A negative cervical tilt angle was defined as the mid-

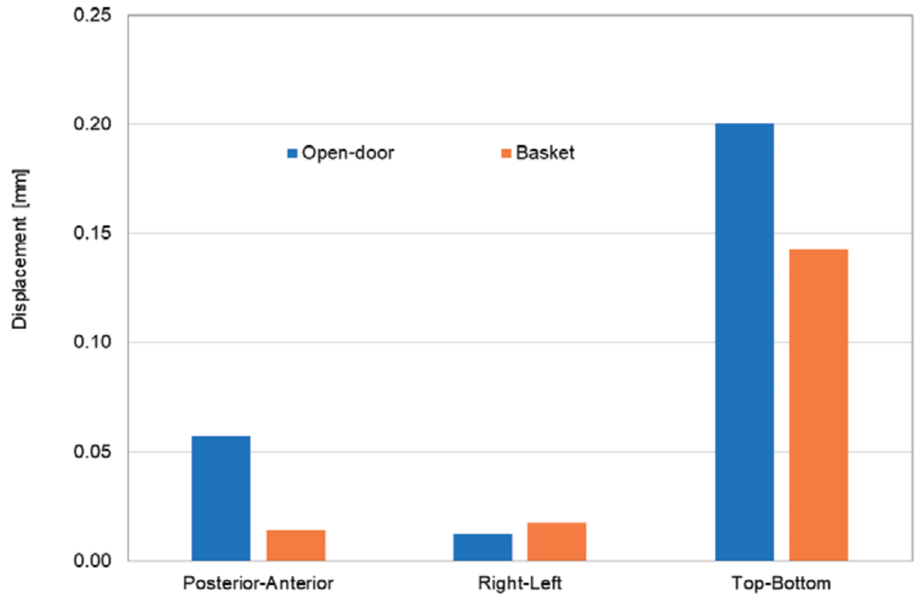

Fig. 3 Maximum displacement of spinous processes in each model under three-directional posterior-to-anterior, right-to-left, and top-to-bottom compression conditions. The Basket model was equivalent to the Open-door model in all three directions.

point of the anterior tubercle of C1 being posterior to the vertical line from the midpoint of the C7 vertebral body. All radiological evaluations were performed using the EGMAIN-EX computerized medical records system (Fujitsu Limited, Tokyo, Japan).

Statistical analysis

JMP version 14 software (SAS Institute, Cary, NC, USA) was used for all statistical analyses. All data are expressed as average ± standard deviation. Statistical comparisons of pre- and postoperative C2-C7 angle or cervical tilt angle were conducted using the paired t-test. A p-value <0.05 was considered as statistically significant.

Statement of ethics

The authors certify that all applicable institutional and governmental regulations regarding the ethical use of clinical data were adhered to for the present study. This retrospective study was approved by the institutional review board (No. 4260). We disclose the information about this clinical study on the website of our department and guarantee the opportunity for refusal (opt-out). Since this study is a retrospective observational study, opt-out disclosure eliminates the need for patient consent.

Results

FEA-equivalent stress histogram

The stress distribution study using CT-based FEA suggested that the stress concentrations and distributions differed between the two models of cervical laminoplasty. Under the PA compression (Fig. 2C, D), the corresponding peak stresses were more observed in the titanium basket plate in the Open-door model than in the Basket model. Under the RL compression (Fig. 2E, F), the corresponding peak stresses were more observed in the titanium basket plate in the Basket model than in the Open-door model. Under the TB compression (Fig. 2G, H), the corresponding peak stresses were similar between the two models.

FEA-maximum displacement of spinous processes

The deformation study suggested that the Basket model was equivalent to the Open-door model in all three directions (Fig. 3). Under PA compression, displacement of the spinous process was 0.0571 mm in the Open-door model and 0.0143 mm in the Basket model. Under RL compression, displacement of the spinous process was 0.0123 mm in the Open-door model and 0.0176 mm in the Basket model. Under TB compression, displacement of the spinous process was 0.2000 mm in the Open-door model and 0.1428 mm in the Basket model.

Clinical image analysis

During follow-up, no patients underwent revision surgery of lift-up basket laminoplasty because of implant-related complications. Radiological outcomes are summarized in Table 2. In the analysis of implant-related complications, Grade 0 was noted in 23 out of 28 (82.1%) cases; Grade 1 in 4 (14.3%); and Grade 2 in 1 (3.6%). No cases suggestive of Grade 3 complications were encountered. The average C2-C7 angle was 9.6° before surgery and remained at 9.5° after surgery. The average cervical tilt angle was 9.0° before surgery and was maintained at 10.5° after surgery. No significant differences in C2-C7 angle or cervi-

Table 2 Radiological outcome of cervical lift-up basket laminoplasty after resection of spinal intramedullary tumors (2014–2019)

Characteristics	N
No. of patients analyzed	28
Average age (years)	46.2 ± 17.7
Gender (male:female)	15:13
Average duration of postoperative follow-up (months)	31.9 ± 16.2
Average no. of laminoplasty	2.5 ± 0.7
Implant-related complications	
Grade 0	23
Grade 1	4
Grade 2	1
Grade 3	0
C2–C7 angle (°)	
Preop	9.6 ± 12.2
Postop	9.5 ± 17.5
Cervical tilt angle (°)	
Preop	9.0 ± 6.0
Postop	10.5 ± 7.2

cal tilt angle were observed between pre- and postoperatively. Five out of 28 (17.9%) cases demonstrated kyphotic changes to the cervical curvature after surgery. Postoperative kyphosis appeared to be more likely in the subgroup with C2 laminoplasty (4/11 cases, 36%) than in the subgroup without it (1/17 case, 6%), although there was no significant difference between them (P = 0.062). The kyphosis tended to complete in several months after the surgery and stabilize thereafter.

Discussion

This CT-FEA suggested that cervical lift-up basket laminoplasty was equivalent to the open-door style. FEA-equivalent stress histograms clearly showed that stress was moderately dispersed around the basket. In the clinical analysis, deterioration of cervical spine curvature was observed in 5 out of 28 (17.9%) cases during postoperative follow-up. However, the average C2-C7 angle or cervical tilt angle after surgery was equivalent to those before surgery. No cases required revision surgery for cervical laminoplasty.

In addition to structural stability, changes in spinal curvature of the cervical spine are the crucial issue in the postoperative management of spinal cord tumors.[3-5,7,8) Asazuma et al. analyzed 51 patients who underwent cervical tumor removal via a single posterior approach of expansive open-door laminoplasty (ELAP), conventional laminectomy, or hemilaminectomy (HL).[3)] They suggested that careful attention to postoperative changes in the spinal curvature is necessary when ELAP is performed, especially if the ELAP involves the C2 level. HL may be the best procedure regarding maintenance of the spinal curvature of the cervical spine. McGirt et al. suggested a high risk of spinal deformity after resection of intramedullary spinal cord tumors in children who underwent laminectomy compared with laminoplasty.[4)] Nori et al. analyzed 54 adult patients who underwent surgery for cervical intramedullary spinal cord tumors.[8)] They suggested that atrophy of the deep extensor muscles (DEMs) of the cervical spine after surgery and detachment of DEMs from the C2 spinous process are directly related to the risk of cervical spinal kyphosis after surgery for cervical intramedullary tumors in adults. Structural analysis as well as clinical radiological evaluation may aid surgeons understand the risk of postoperative implant-related troubles or cervical malalignment.

FEA was first developed in the 1950s for analyzing structural problems in engineering fields and was then applied to biomechanical analyses, particularly in the orthopedic field, in the 1970s.[16)] Initially, FEA was not widespread for the study of spinal biomechanics, which were more complex in structure. However, with subsequent advances in computer technology, the application of FEA to the study of spinal structure and biomechanics has become widespread since the 1990s.[17,18)] A recent study by Johannesdottir et al. indicated the prediction of vertebral fracture using a high-quality FE model and CT-based bone density.[19)] In the biomechanical evaluation using CT-FEA, the three-dimensional shape of the bones and implants can be analyzed accurately. It is also possible to arbitrarily change the site and direction of the load on the implant. Stress distributions around the implant can then be visualized. In the early period, spinal implant research using FEA was applied to the study of posterior lumbar fixation, including pedicle screws. Goel et al. reported a comparative study using FEA between three types of posterior lumbar fixation devices.[20] The utility of FEA has since been confirmed by many authors assessing the biomechanical strength of pedicle screws.[21-24] Xie et al. performed a biomechanical comparison of laminectomy, HL, and unilateral multilevel interlaminar fenestration for the surgical treatment of cervical intradural tumors using FEA.[25] They suggested that the posterior bone elements play a slight role in spinal stability after removing the attached ligaments. Recently, Song et al. reported an FEA for the biomechanics of oblique lumbar interbody fusion with various fixation options.[26] They successfully and accurately evaluated the biomechanical properties by constructing detailed finite element models separated into cortical bone, cancellous bone, nucleus pulposus, annulus fibrosus, and even each ligament. The recent development of FEA focusing on spinal structures is remarkable, and the realization of structural analyses close to biologically real environments is definitely desirable. However, it should be noted that the setting of conditions in FEA is not always similar to that of living tissue.

The reconstruction of cervical laminae after removal of an intramedullary tumor varies from simple laminectomy, laminoplasty, or posterolateral fusion. The method presented here is by no means standard, but one of the options. The purpose of this study is the biomechanical assessment of cervical lift-up basket laminoplasty compared to the open-door style. Since this FEA was based on data from a single case, making a universal interpretation is clearly not appropriate, and analysis of a larger number of cases is absolutely necessary. Values calculated by CT-FEA are only predicted values, not real values. In addition, the surrounding soft tissues, including muscle layers and ligamentous structures, that support the cervical spine were not included in our analysis. The setting of analysis conditions is not always close to the real condition. However, the biomechanical assessment by CT-FEA appears to be one of the evaluation methods in this medical field. The clinical radiological evaluation in this study was a retrospective analysis from a single institute. A clinical analysis as collaboration between multiple centers is desirable. Careful judgment should be made from a long term postoperative perspective. Although this study has some of the above study limitations, it suggested that the biomechanical assessment of cervical lift-up basket laminoplasty was equivalent to the open-door style.

Conclusion

This is the imaging study to focus on the structural reliability of our unique method of cervical lift-up basket laminoplasty. CT-based FEA demonstrated that cervical lift-up basket laminoplasty appears structurally equivalent to the open-door style. Clinical radiological evaluation suggested that cervical lift-up basket laminoplasty after resection of spinal intramedullary tumors of the cervical spine is practical and safe, although the stability in the long term after surgery needs to be further explored.

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Conflicts of Interest Disclosure

All authors who are members of the Japan Neurosurgical Society (JNS) have registered online Self-reported COI Disclosure Statement Forms through the website for JNS members.

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