Effect of posterior decompression extent on biomechanical parameters of the spinal cord in cervical ossification of the posterior longitudinal ligament

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Abstract
Ossification of the posterior longitudinal ligament is a common cause of the cervical myelopathy due to compression of the spinal cord. Patients with ossification of the posterior longitudinal ligament usually require the decompression surgery, and there is a need to better understand the optimal surgical extent with which sufficient decompression without excessive posterior shifting can be achieved. However, few quantitative studies have clarified this optimal extent for decompression of cervical ossification of the posterior longitudinal ligament. We used finite element modeling of the cervical spine and spinal cord to investigate the effect of posterior decompression extent for continuous-type cervical ossification of the posterior longitudinal ligament on changes in stress, strain, and posterior shifting that occur with three different surgical methods (laminectomy, laminoplasty, and hemilaminectomy). As posterior decompression extended, stress and strain in the spinal cord decreased and posterior shifting of the cord increased. The location of the decompression extent also influenced shifting. Laminectomy and laminoplasty were very similar in terms of decompression results, and both were superior to hemilaminectomy in all parameters tested. Decompression to the extents of C3–C6 and C3–C7 of laminectomy and laminoplasty could be considered sufficient with respect to decompression itself. Our findings provide fundamental information regarding the treatment of cervical ossification of the posterior longitudinal ligament and can be applied to patient-specific surgical planning.

Keywords
Spine biomechanics, modeling/simulation, orthopedic procedures, clinical outcome prediction, finite element modeling/analysis

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Introduction
Ossification of the posterior longitudinal ligament (OPLL) is a common cause of cervical myelopathy due to compression of the spinal cord, especially in Asian populations, and severe OPLL may lead to cervical cord damage and various neurological deficits.1 Patients with OPLL usually require decompression surgery performed from either an anterior or posterior approach. Anterior surgical approaches have demonstrated good outcomes for segmental OPLL due to direct removal of ossified ligaments.2–4 Posterior approaches, which achieve decompression via posterior shifting of the cord, are feasible options for OPLL that extends more than two or three levels (e.g. continuous-type OPLL), and this approach is less technically challenging, more effective, and safer, especially for old patients.1,5,6 There are several posterior approaches for indirect decompression of the spinal cord, including laminectomy, in which posterior spinal elements are

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removed, and laminoplasty, in which the lamina is opened. Hemilaminectomy is another approach that preserves ligaments and posterior elements as much as possible to maintain stability.7

In posterior surgical approaches, the extent of decompression needed is left to the discretion of the operating surgeon and is typically based on clinical and radiological factors such as duration and severity of myelopathy, age, pre-operative kyphosis, occupying ratio and type of ossification, and possibility of post-operative OPLL progress.1,8–11 Due to the difficulty of directly evaluating decompression, several studies have suggested that posterior shifts of the spinal cord can be used as a surrogate measure, as greater shifts are associated with better clinical outcomes after posterior decompression.11,12 Several experimental and clinical studies observed that larger extents of decompression resulted in more spinal cord shift.9–11,13,14 However, extensive decompression may cause excessive posterior shifting of the spinal cord, which can result in complications such as C5 palsy, spinal curvature changes, or spinal instability, which require additional surgical treatment for fusion and posterior stabilization.1,13,15 Thus, there is a need to better understand the optimal surgical extent with which sufficient decompression without excessive posterior shifting can be achieved; however, few quantitative studies have clarified this optimal extent for decompression of cervical OPLL.

Due to limitations associated with experimental studies of the cervical spine and spinal cord, finite element (FE) analysis has been used to investigate the relationship between mechanical parameters and neurological deficits in order to understand spinal cord injury (SCI). FE models of the spinal cord have been developed to analyze biomechanical features such as stresses and strains caused by the ossified ligaments in the spinal cord that may result in deficits or injuries.16–20 They have also been used to investigate mechanical stresses in the spinal cord after laminectomy followed by dekyphosis for segmental OPLL in a thoracic model.21 However, few studies have focused on predicting the stresses and strains that arise within the spinal cord after different types and extents of posterior decompression of cervical OPLL. In this study, we used validated FE modeling of the cervical spine and spinal cord which included white matter, gray matter, dura mater with nerve roots, DLs, and cerebrospinal fluid (CSF)20,22 to investigate the effect of posterior decompression extent on changes in stress, strain, and posterior shifting that occur with three different surgical methods (laminectomy, laminoplasty, and hemilaminectomy).

**Materials and methods**

The FE model used in this study was developed based on our previously validated model, the details of which can be found elsewhere.20,22 An FE model of the human C2–C7 cervical spine was reconstructed from the computed tomography (CT) images of a healthy subject (25 years old, 175 cm, and 70 kg) at 1-mm intervals. The FE model of the spinal cord consisted of white matter, gray matter, dura mater with nerve roots, DLs, and a CSF layer. The model was developed using quantitative measurements of the human spinal cord (Figure 1).23,24 The dural sheath was placed approximately 2.5 mm from the cord, since the CSF layer in the human cervical spine has been shown to be at a distance of 1.5–4.0 mm experimentally.25 The FE model of the cervical spine with the spinal cord included 109,861 nodes and 232,303 elements, excluding fluid elements. Fluid elements were modeled as Eulerian elements, an arbitrary collection of cubic elements that fully encompasses the region of fluid material during the analysis. The volume between the dural sheath and cord was filled with Eulerian material, and the interaction between the fluid material and solid bodies was coupled.
with the Eulerian–Lagrangian analysis method using ABAQUS (ABAQUS©, ABAQUS Inc., Providence, RI, USA). Each vertebral body was modeled as a rigid body to reduce the computational cost, as they had little influence on parameters in the spinal cord.

Material properties of the spinal cord, such as the nonlinear, hyperelastic stress–strain curve of the white and gray matter, were obtained from an experimental study. The dura mater with nerve roots were assumed to represent a single tangent modulus derived from the study by Persson et al. The DLs were modeled based on an experimental study as 22 triangular extensions, using link elements at each spinal level that attached laterally from the cord to the dura mater, and material property was obtained from a previous study. Material properties of CSF as a Newtonian fluid were derived from previous literature.

Three types of posterior decompression models for laminectomy, laminoplasty, and hemilaminectomy were developed based on conventional surgical protocols with different extent of decompression (Figure 2). In the laminectomy model, the spinous process and lamina were removed, while the facet joints remained intact. In the laminoplasty model, the open-door method was employed; the lamina was opened by 12 mm, which was the same distance reported in a previous clinical study. In the hemilaminectomy model, one side of the lamina and spinous process was removed. The extent of decompression ranged from one to five levels: C5, C4–C5, C4–C6, C3–C6, C4–C7, and C3–C7 for each types of model, where the continuous OPLL placed through the C4–C6 vertebral bodies. The OPLL was modeled as a simple rigid body model, and an OPLL occupying ratio of 20%–60% was imposed to the spinal cord based on plain radiographic findings. The OPLL occupying ratio was defined as the ratio of OPLL thickness to the anterior–posterior diameter of the spinal canal.

Under various OPLL occupying ratios, the von-Mises stress and maximum principal strain in the spinal cord as well as the posterior spinal cord shift were analyzed for pre-operative and various posterior decompression models using FE analysis (ABAQUS). The posterior shift of the spinal cord was defined as the distance between the posterior edge of the vertebral body level and the posterior edge of the spinal cord at the maximum compressed level. The von-Mises stress, maximum principal strain, and posterior shift of the spinal cord were chosen as biomechanical parameters related to the spinal cord damages based on previous experimental and clinical studies, where it was shown that von-Mises stress and maximum principal strain were correlated to cord tissue damage and that the posterior shift of the spinal cord was associated with clinical outcomes of posterior decompression.

Results
The maximum von-Mises stress in the cord decreased as the extent of posterior decompression increased,
regardless of the occupying ratio and the type (Figure 3(a)). Stress dramatically decreased in three-, four-, and five-level decompression by laminectomy and laminoplasty, as the maximum stresses at the 60% occupying ratio of OPLL was 210 kPa in the pre-operative model, while it was less than 20 kPa in C4–C6 and C4–C7 and about 7 kPa in C3–C6 and C3–C7 of both laminectomy and laminoplasty. In contrast, the reduction in maximum von-Mises stress was less profound in hemilaminectomy when compared to laminectomy and laminoplasty; the maximum stress at the 60% occupying ratio were approximately 60 kPa in C4–C6 and C4–C7 and 50 kPa in C3–C6 and C3–C7, although the maximum value was reduced by 70% in C3–C6 and C3–C7 in comparison to the pre-operative model.

Similarly, the maximum principal strain in the cord decreased as the extent of decompression increased, regardless of the occupying ratio. This finding was especially pronounced in decompression by laminectomy and laminoplasty, but not as much so by hemilaminectomy (Figure 3(b)). The maximum strains at the 60% occupying ratio of OPLL was 0.40 in the pre-operative model, while it was less than 0.25 in C4–C6 and C4–C7 and 0.18 in C3–C6 and C3–C7 in both laminectomy and laminoplasty.

The posterior shift of the spinal cord was also elevated as the extent of decompression was expanded (Figure 4). Results showed that laminectomy and laminoplasty had greater posterior shifts of the spinal cord than hemilaminectomy; posterior shifts were approximately twice as large in laminectomy and laminoplasty compared to hemilaminectomy. The maximum posterior shifts at the 60% occupying ratio of OPLL were above 3 mm in C3–C6 and C3–C7 of laminectomy and laminoplasty.

In comparing the distribution of stress in the sagittal view, both laminectomy and laminoplasty decompression showed sufficient subarachnoid space, especially in extensive decompression levels such as C3–C6 and C3–C7, whereas hemilaminectomy showed insufficient subarachnoid space at all extents of decompression (Figure 5). The maximum stress occurred at the rostral and caudal edge of the OPLL extent (C4 and C6) in one- to three-level cases, regardless of the posterior approach. In addition, C3–C6 showed a superior subarachnoid space to C4–C7 in maximum stress and

![Figure 3. (a) von-Mises stress and (b) maximum principal strain in the cord at the 20%–60% occupying ratio of OPLL in the pre-operative model and posterior decompression models.](image-url)
strain comparisons. In the transverse view of the hemilaminectomy, the maximum stress occurred at the lateral column and the cord was shifted obliquely.

Discussion

Our results suggest that enlargement of the extent of posterior decompression is associated with greater reduction in stress and strain in the spinal cord, as well as improved posterior shifting of the spinal cord and subarachnoid space of the canal. These findings are consistent with previous clinical studies. Sodeyama et al.11 demonstrated that in patients who have undergone laminoplasty, extension of posterior decompression to one level above or below compressive lesions results in a greater posterior shift of the spinal cord. Hatta et al.9 reported that extensive laminoplasty results in greater posterior spinal cord shift than one- or two-level selective laminoplasty. Kong et al.10 found that the posterior shift was larger in laminoplasties performed from C1 to C7 than from C3 to C7. Tsuji et al.14 found that the posterior space of the spinal cord enlarges as the number of opened laminae in posterior decompression increases. Moreover, we found that maximum stress in the cord decreased by 30%–90% from one to five levels of decompression by laminectomy, consistent with Okayama et al.,21 who reported that stress decreases by 52.3% after laminectomy. Greater stress occurred at the rostral and caudal edge of the OPLL extent, regardless of the type of posterior approach, which is consistent with the clinical study by Koyanagi et al.,40 which showed that SCI occurs frequently at the disk level or at the caudal edge of the OPLL extent in continuous-type OPLL.

We found that laminectomy and laminoplasty are similar in terms of stress, strain, and posterior shifting of the spinal cord, consistent with a report of Xia et al.41 demonstrating that posterior movements of the spinal cord are similar after laminectomy and laminoplasty. In contrast, the stress and strain reductions of hemilaminectomy differed from the values of laminectomy and laminoplasty due to maximum values at the lateral column arising from lateral decompression of the spinal cord. Liu et al.7 performed multilevel hemilaminectomy with posterior fixation and showed good clinical outcomes for multilevel continuous and mixed cervical OPLL, whereas Singh et al.42 stated that hemilaminectomy does not decompress enough to provide good results. Our findings suggest that hemilaminectomy is inferior to laminectomy and laminoplasty in terms of cord decompression.

The C3–C6 and C3–C7 in the laminectomy and laminoplasty at the 60% occupying ratio of OPLL had a maximum posterior shift of greater than 3 mm, which was associated with positive clinical outcomes after laminoplasty11 and which showed substantial reductions in stress and strain. Thus, posterior shifting, which has been a parameter used to represent the degree of decompression, could also be considered correlated to mechanical parameters, such as stress and strain in the cord, particularly with respect to spinal cord damages from a biomechanical viewpoint. In addition, C3–C6 and C3–C7 might be the sufficient extent of posterior decompression in terms of stress and strain in the cord and the posterior shift of the cord. However, excessive extent of decompression may cause complications such as C5 palsy and spinal instability.1,13,15,43 Iwasaki et al.8 showed that cervical alignment changes when the surgical level extends from C2 to C7, although laminoplasty is effective and safe for patients with an occupying ratio below 60%. Sakaura et al.44 reported a lower recovery rate and a higher incidence of axial neck pain in C3–C7 than in C3–C6 in laminoplasty. Therefore, decompression itself, as well as clinical and surgical factors, such as the recovery rate, alignment change, or OPLL progress, needs to be carefully considered while pre-operatively deciding the surgical extent of the posterior decompression for the cervical OPLL as previous studies suggested.1,8–11

The C3–C6 and C3–C7 models used in both laminectomy and laminoplasty showed very close stresses, strains, and posterior shifts. The C4–C6 and C4–C7
models showed this same phenomenon, while the C3–C6 model was superior to the C4–C7 model in all parameters. Because the C7 vertebra was separated from the ossified ligament region, C4–C6, as shown in Figure 2, C7 seemed to have little effect on the decompression in terms of the stress, strain, and posterior shift. This result suggests that both the number of levels involved in posterior decompression and the location of the decompression extent are important factors required for achieving sufficient decompression and thus should be carefully considered when planning the extent of decompression.

There are several limitations to our study. Only continuous-type OPLL in C4–C6 of a neutral posture was investigated, although previous studies have reported that alignment of the cervical spine, as well as range and type of OPLL, affects posterior shifting and decompression of the spinal cord.\textsuperscript{8,45,46} Material properties utilized in this study were obtained from an experimental study,\textsuperscript{26} providing separate stress–strain curves for the white and gray matter of the bovine spinal cord as in previous modeling studies.\textsuperscript{17–20} The fluid was modeled as initially being between the cord and dural sheath, and fluid flow was not incorporated since it has been shown to have minimal impact on the tested parameters.\textsuperscript{47} Therefore, future studies will be necessary to investigate the various types of OPLL with different cervical alignments, such as more lordotic or kyphotic, and different postures, such as flexion and extension. Further studies will also be needed to improve FE models of the spinal cord, ossified ligaments, and the cervical spine using patient-specific anatomic and material properties, all of which will enhance the confidence of this study.

In conclusion, we investigated the effect of the extent of posterior decompression on the spinal cord in three types of models for continuous-type cervical OPLL of C4–C6. As posterior decompression extended, stress and strain in the spinal cord decreased and posterior shifting of the cord increased. The location of the decompression extent also influenced shifting, depending on the patient’s anatomy. Laminectomy and laminoplasty were very similar in terms of decompression results, and both were superior to hemilaminectomy in all parameters tested. Decompression to the extents of C3–C6 and C3–C7 of laminectomy and laminoplasty could be considered sufficient due to the substantial decrease in the stress and strain in the spinal cord and a posterior cord shift greater than 3 mm with respect to decompression itself. In order to determine the optimal extent of decompression for cervical OPLL, clinical and surgical factors, such as the recovery rate, alignment change, or OPLL progress, also need to be carefully considered. Our findings provide fundamental information regarding the treatment of cervical OPLL and can be applied to patient-specific surgical planning in the future.

![Figure 5](image-url) Distribution of von-Mises stress in the spinal cord at the 60% occupying ratio of OPLL: (a) laminectomy, (b) laminoplasty, and (c) hemilaminectomy.

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