BIOMECHANICAL EFFECTS OF LAMINOPLASTY AND LAMINECTOMY ON THE STABILITY OF CERVICAL SPINE

INTRODUCTION

**Relevant Anatomy:** The spinal column is made up of series of motion segments, each of which contains an intervertebral disc and its two adjacent facet joints. The resultant spinal canal houses the spinal cord and nerve roots, while the structural arrangement is well suited to weight-bearing and diverse head movements (e.g., rotate side to side, flexion and extension). The cervical spine is made up of the first seven vertebrae in the spine. A typical vertebra consists of an anterior body and a posterior ring made of articular, transverse, and spinous processes. The cervical spine also features a complex arrangement of ligaments to supplement its structure and mobility. Figure 1 shows the general anatomy of a cervical vertebra.

Cervical spinal stenosis is the most common spinal cord disorder in persons more than 55 years of age in North America and perhaps in the world [1]. It is a chronic degenerative condition of the cervical spine that results in the reduction of spinal canal diameter and thereby compresses the spinal cord and the associated nerve roots. Surgical options can be broadly classified into two categories namely, anterior and posterior approaches. This study focuses on posterior based approach (i.e. laminectomy or laminoplasty) which is considered when multiple levels of the spine have to be decompressed or when most of the cord compression results from posterior pathological conditions. Historically, laminectomy has been regarded as the standard treatment for multi-level cervical stenosis and myeloradiculopathy. However, the results of the procedure were universally unsuccessful with complications such as segmental instability and postoperative kyphosis [2]. Because of such concerns, laminoplasty was developed as an alternative to laminectomy. It is mainly intended to relieve pressure on the spinal cord while
maintaining the stabilizing effects of the posterior elements of the vertebrae. Different laminoplasty techniques have been described which vary by where the hinge and opening of the lamina are developed. They can be broadly classified into two types namely open door (ODL) and double door laminoplasty (DDL). Open door laminoplasty includes opening of the lamina from either left or right side with the contralateral side acting as hinge. In double door laminoplasty, the door is opened in the midline and the hinges are created bilaterally thereby resulting in symmetric opening (Figure 3 and Figure 4).

Achieving and maintaining an increased sagittal diameter after cervical laminoplasty is probably one of the most important criteria to facilitate neurological recovery. Laminar opening can be maintained using sutures, autograft/allograft bone, hydroxyapatite (HA) spacers and laminoplasty plates. The current study employs titanium plate and screw system for ODL and HA spacers for DDL. The use of miniplates from cranial fixation systems for cervical laminoplasties was first described by Frank et al. and later O’Brien et al. quantified the increased spinal canal area using this technique [3, 4]. No intraoperative and postoperative complications were observed [5]. A retrospective study performed on 104 patients with instrumented ODL proved the technique to be a safe and reliable method for preventing progression of myelopathy with multilevel involvement. There was no sign of fatigue failure or loosening of plates in this large series of patients, thereby avoiding the revision for fixation failure which could have led to the closure of lamina [6]. Shaffrey et al. performed a modified open door laminoplasty with allograft bone and titanium miniplates and reported good short-term results in terms of neurological outcome in younger patients with congenital spinal stenosis [7]. Hence, with the increasing laminoplasty market, there is a need to evaluate the effect of these implants on the biomechanical stability of the spine.
Compared to the open door laminoplasty, double-door laminoplasty has some theoretical advantages like symmetrical expansion, and the potential for posterior fusion with a bone graft bridge between the spinous process. It was reported that the group of patients with HA spacers effectively maintained the range of motion compared to the group with autogenous iliac grafts [8]. However, inadequate contact between the spacer and bone was one of the initial problems, resulting in the instability of the spacer and restenosis of the spinal canal. During laminar opening, the widened space was observed to be trapezoidal in both axial and frontal planes in a finite element study conducted by Hirabayashi et al [9]. The study also reported increased lateral deviation of the spinous process with the hinge than without the hinge, and thereby suggesting the importance of creation of hinge during laminar opening. Hence, most of the currently available spacers are trapezoidal in shape to accommodate the contour of the spinous process.

**Significance:** The external and internal behavior of the spine after laminoplasty has been of great interest to the clinicians and biomechanical researchers. Understanding the effect of this surgical procedure on the biomechanics of the spine helps in better treatment and prevention of spinal instability. To date, numerous clinical studies have been done to see the effect of multi-level laminoplasty on the kinematics of spine. But, very few in vitro studies and to our knowledge, this is the first computational study done to see the biomechanical response of the spine to the surgical procedure. The current study emphasizes on simulating laminoplasty and laminectomy in multi-level (C3-C6) finite element models. Moreover, the main aim of laminoplasty is create a stable laminar arch to preserve the laminar opening. As hinge failure is a commonly encountered problem during laminoplasty, it is necessary to understand the process of bone remodeling post laminoplasty. Hence, the study also implements a computer simulation method to predict bone remodeling in accordance with Wolff’s Law.
METHODS:

Specific Aim 1: Simulation of laminectomy and laminoplasty techniques for C3-C6 levels in an intact C2-T1 finite element model.

In this study, a detailed validated subject-specific 3D finite element model of the cervical spine (C2-T1) was used [10, 11]. The vertebral bodies were segmented from the CT images of the cadaveric spine and were meshed with hexahedral elements using multi-block meshing technique (IA-FeMesh). The vertebral body was divided into cortical and cancellous regions and a Young’s modulus of 10GPa and 450MPa was assigned respectively. The model includes clearly defined annulus and nucleus regions, five major spinal ligaments namely anterior longitudinal ligament, posterior longitudinal ligament, ligamentum flavum, interspinous and capsular ligaments. Additionally, the facet gap was modeled using the tabular pressure-overclosure relationship in ABAQUS finite element software (Simulia, Providence, RI). Validation of the model is essential but extremely difficult due to the varying material properties along the length of the specimen. The current intact model was validated by comparing the finite element predictions with subject-specific experimental data under similar loading and boundary conditions. Subsequently, the intact C2-T1 finite element model was modified to simulate the surgical procedure of laminectomy and laminoplasty at levels C3-C6; which are the most commonly observed levels of stenosis. As an example, the procedure is explained clearly for C5 vertebrae through figures.

Simulation of Laminectomy: The lamina, spinous process and the associated ligaments (interspinous ligaments, ligamentum flavum) were removed. Facet joints were kept intact (Figure 2).
Simulation of ODL: A bicortical cut was simulated along the junction of the lamina and the lateral mass of the intact vertebral mesh by completely removing a layer of elements. On the contralateral side, a hinge of approximately 3-4mm was created along the junction of the lamina and lateral mass by removing elements representing the unicortical layer (Figure 3(a)). The spinous processes of the involved vertebrae (C3-C6) along with the interspinous ligaments were resected. Additionally, the ligamentum flavum at the unaltered levels (C2-C3 and C6-C7) was also cut partially on the open side of the lamina to allow laminar opening. Two screw holes in the lateral mass and one hole in the lamina were created based on the desired plate position. Care was taken to angle the screws away from the facet joints. The lamina of each vertebra, C3-C6, was opened towards the hinge by applying a uniform load (Figure 3(b)). The laminar opening space which is the distance between the lateral mass and the cut end of the lamina can vary from 8 to 12mm depending on the patient’s compressive pathology. We chose a laminar opening of 10mm for all the levels C3-C6. Our Previous studies on single level laminoplasty have shown an increase of 56% in spinal canal area and 35% in sagittal canal diameter at C5 level [12]. The stresses developed in the vertebra while opening the lamina tend to close it back and hence have to be stabilized using plates and screws (Figure 3(c)). The titanium (Ti) plate and screws were meshed with hexahedral elements using IA-FEMesh and were assigned an elastic modulus of 116GPa and Poisson’s ratio of 0.3. Small sliding contact was formulated at the interface between the bone and the laminoplasty constructs. Additionally, the surfaces of the bone/screw and the screw/plate were tied during the analysis.

Simulation of DDL: Two bilateral hinges at the junction of lateral mass and lamina were created by removing the elements corresponding to the unicortical layer. Hinges should not be too medial or too lateral as too medial may result in insufficient enlargement of the spinal canal,
and too lateral makes opening the split lamina difficult and may also cause facet fusion. The spinous process is sagitally split until a laminar opening of 10mm is obtained. Laminar opening is defined as the distance between the basal part of spinous process. The technique also involves resection of interspinous ligaments at all the involved levels and partial removal of the ligamentum flavum at the midline from C2 to C7 to allow for laminar opening. A 10mm trapezoidal shaped hydroxyapatite (HA) spacer, meshed with hexahedral elements was used to stabilize the lamina in the open position. The bony union observed in many clinical studies between the HA spacers and spinous process was simulated by using the TIED command in ABAQUS [13].

Figure 6 shows the simulated laminoplasty and laminectomy models.

**Flexibility Test:** The intact and all three surgically simulated models (namely ODL, DDL and laminectomy) were tested using a pure moment of 2Nm under physiologic flexion/extension (±MX), right/left lateral bending (±MZ), and right/left axial rotation (±MY) modes. The inferior nodes of the T1 vertebra were fixed in all directions and a moment of 2Nm was applied on the superior surface of C2. The analysis was performed using the finite element software ABAQUS 6.9. Ranges of motion, stresses in the annular regions of the intervertebral discs and cortical regions of the vertebral bodies were analyzed and compared to that of the intact model.

**Specific Aim 2: Application of adaptive bone remodeling theory to cervical laminoplasty**

Literature presents several attempts made by various authors to quantify the bone remodeling process. The theory of adaptive elasticity was developed to predict the behavior of bone from one loading configuration to another by assuming a site-specific homeostatic equilibrium strain state. Weinans et al. postulated the rate of change of apparent density of the bone at a particular location in terms of mechanical stimulus like strain energy density (SED)
The difference between the actual SED (i.e. S), and the homeostatic SED (i.e. S₀) is the driving force for bone remodeling. As proposed by Carter et al., a lazy zone was introduced so that a certain threshold level is exceeded before the bone reacts [15]. We chose to use a lazy zone of 35% based on the earlier remodeling studies done on spine [16]. Equation 1 describes the nonlinear relationship between the mechanical stimulus and rate of change of density featuring the lazy zone (1±s) that represents the minimum effective strain.

\[
\frac{d\rho}{dt} = \begin{cases} 
B(S-(1+s) S₀) & S > (1+s) S₀ \\
0 & (1-s) S₀ \leq S \leq (1+s) S₀ \\
B(S-(1-s) S₀) & S > (1+s) S₀ 
\end{cases}
\]

\[
S = \frac{SED}{\rho}
\]

B: Remodeling Rate  
s: Half width of lazy zone interval
S: Remodeling stimulating signal  
S₀: Reference stimulating signal

Assuming that the behavior of remodeling is similar for all the altered levels, we chose to implement remodeling at the C5 vertebra only. The remodeling code was written in FORTRAN 90. The integration between the remodeling code and finite element model is shown in Figure 5.

The objective function is defined as F/N; 

\[
F = \sum | S_i - (1 \pm s) S_{0,i} |
\]

N=Number of elements satisfying the objective criteria

**Intact Model:** Intact finite element model of C2-T1 was taken and a compressive load of 50N was applied on the top of the C2 surface. Subsequently, the bone remodeling algorithm was applied to C5 vertebrae to determine optimal bone density distribution. The reference value (S₀) for each part was determined as the average SED value of all elements under compression. Hence S₀ is constant for all elements. If the objective criterion was satisfied, the material properties were updated and the algorithm was repeated until convergence was met.

**Laminoplasty Model:** C2-T1 open door laminoplasty model was taken and bone remodeling algorithm was implemented at C5 only. The site-specific SED values from the
optimized intact model serve as the reference SED values for the laminoplasty model. Hence $S_0$ is specific for each element. Hinge failure was simulated by removing a single row of elements where maximum stress concentration occurred. The model was run under a 50N compressive load and remodeling was performed until convergence was met.

**RESULTS:**

As mentioned earlier, the main aim of the laminoplasty technique is to hold the lamina in the open position without failure to successfully decompress the spinal cord. The laminoplasty constructs namely the screws and plates of ODL and the HA spacer of DDL were evaluated for their stability. During all the six loading modes, the von Mises stresses in the plate and screw were within the yield strength of the Ti implant i.e. 917MPa.

Figure 7 compares the percent changes in the total range of motion (C2-T1) after laminoplasty and laminectomy. The surgical procedures had significant effect in flexion while minimal changes were observed in the other loading modes. ODL resulted in a 5.4% increase in C2-T1 range of motion during flexion, while less than a 5% change was observed in the other loading modes. DDL resulted in a significant 20% increase in the overall range of motion during flexion with marginal changes in other loading modes. Laminectomy resulted in a substantial 57.5% increase in the total range of motion during flexion only with minimal changes in other directions.

Considering the change in intersegmental rotations during flexion: After ODL, there was a 39% and 20% increase in the motion at C2-C3 and C6-C7, while no substantial changes were observed at the altered levels. The percent increase in the motion after DDL varied from 4.3% to 34.6%. Laminectomy at C3-C6 led to significant increase in motion across all the levels from
C2-C3 to C6-C7. These changes in the intersegmental rotations could be attributed to the ligament resection at those levels.

A significant increase in the cortical stresses of the vertebral bodies was observed at levels C3-C6 after the surgical procedures, with the posterior regions demonstrating higher stresses than the anterior regions. DDL recorded higher stresses than ODL. This could be due to the increased stresses developed in the vertebrae with opening both the lamina as opposed to single lamina in ODL. Figure 8 shows the percent changes in the annular stresses of the intervertebral discs after the simulated surgical procedures during flexion. Significant changes were observed during flexion and correlated to the changes in the intersegmental rotation where unaltered levels were affected after ODL and altered levels showed substantial increases after DDL and laminectomy.

Figure 9(a) shows the density distribution for an optimal intact configuration under compressive load. It resulted in the increase of the density values in the posterosuperior, mid-inferior cortical and pedicle regions. These changes in the internal bone density can lead to changes in the external morphology like thickening of the endplates in those regions. Figure 9(b) shows the density distribution in a converged C5 vertebra after ODL. Since, the model was run only under compression, most of the posterior elements were unloaded and as a result no major differences in the density distribution were observed. The model shows a slight increase in the density values at the hinge region suggesting bone formation.

**DISCUSSION and CONCLUSION:**

Numerous clinical studies have addressed the influence of multi-level laminoplasty on the kinematics of spine. To our knowledge, currently there exists no other computational study that compares the biomechanical effects of the two laminoplasty techniques. The results from the
current finite element predictions suggest the preservation of range of motion after open door laminoplasty that corresponds well with the previous in vitro studies [17]. Kubo et al. showed an inclination towards increased motion at all levels, which was also observed in the current study after DDL, thereby explaining the role of lamina-ligamentum flavum complex in the stability of spine [18]. As hypothesized, laminectomy resulted in a significant increase in motion during flexion while no significant differences were observed in other loading modes as no facet injury was simulated in the current study. The significant increase in the cortical stresses of the vertebral body after both the laminoplasty and laminectomy procedures may be clinically correlated to the degenerative process. To further augment/validate the finite element studies, we are currently performing flexibility tests on cadaveric cervical specimens after laminoplasty and laminectomy.

The greatest density changes in the optimized intact vertebrae occurred posteriorly and mainly in the superior and inferior endplate regions. This is in accordance with the work done by other authors, where the center of the endplate and the region between the endplates were less dense compared to other regions of the vertebrae [16, 19]. It was observed that compression did not have any major affect on the posterior elements that were significantly altered by laminoplasty. Hence, we are currently extending bone remodeling to other loading conditions like flexion and extension to get a better representation of density changes. It can be concluded that adaptive bone remodeling theory can be applied to understand the process of bone remodeling especially at the hinge region following surgical simulations like open door laminoplasty.
**Figures**

Figure 1: Anatomy of Cervical spine

Figure 2: Laminectomy on C5 vertebrae

**OPEN DOOR LAMINOPLASTY:** Figure 3 (a): C5 vertebrae showing hinge and open side of the lamina (b): C5 vertebrae showing the Laminar opening (c) C5 vertebra stabilized with plates and screws

**DOUBLE DOOR LAMINOPLASTY**

Figure 4: C5 vertebra stabilized with HA spacer

Figure 5: Bone Remodeling Algorithm
Figure 6: C2-T1 Models (a) Laminectomy Model (b) Open Door Laminoplasty (c) Double Door Laminoplasty

Figure 7: Percent changes in C2-T1 range of motion after ODL, DDL and laminectomy

Figure 8: Percent changes in the annular stresses during flexion

Figure 9: (a) Density distribution in an optimized intact C5 vertebra (b) Density distribution in a converged C5 vertebra after ODL
References


