Basic Science

Finite Element Analysis of the Effect of Epidural Adhesions

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Background: It is well documented that epidural adhesion is associated with spinal pain. However, the underlying mechanism of spinal pain generation by epidural adhesion has not yet been elucidated.

Objectives: To elucidate the underlying mechanism of spinal pain generation by epidural adhesion using a two-dimensional (2D) non-linear finite element (FE) analysis.

Study design: A finite element analysis.

Setting: A two-dimensional nonlinear FE model of the herniated lumbar disc on L4/5 with epidural adhesion.

Methods: A two-dimensional nonlinear FE model of the lumbar spine was developed, consisting of intervertebral discs, dura, spinal nerve, and lamina. The annulus fibrosus and nucleus pulpous were modeled as hyperelastic using the Mooney-Rivlin equation. The FE mesh was generated and analyzed using Abaqus (ABAQUS 6.13.; Hibbitt, Karlsson & Sorenson, Inc., Providence, RI, USA). Epidural adhesion was simulated as rough contact, in which no slip occurred once two surfaces were in contact, between the dura mater and posterior annulus fibrosus.

Results: The FE model of adhesion showed significant stress concentration in the spinal nerves, especially on the dorsal root ganglion (DRG). The stress concentration was caused by the lack of adaptive displacement between the dura mater and posterior annulus fibrosus. The peak von Mises stress was higher in the epidural adhesion model (Adhesion, 0.67 vs. Control, 0.46). In the control model, adaptive displacement was observed with decreased stress in the spinal nerve and DRG (with adhesion, 2.59 vs. without adhesion, 3.58, $P < 0.00$).

Limitations: This study used a 2D non-linear FE model, which simplifies the 3D nature of the human intervertebral disc. In addition, this 2D non-linear FE model has not yet been validated.

Conclusion: The current study clearly demonstrated that epidural adhesion causes significantly increased stress in the spinal nerves, especially at the DRG. We believe that the increased stress on the spinal nerve might elicit more pain under similar magnitudes of lumbar disc protrusion.

Key words: Finite element, epidural adhesion, spinal pain, adhesiolysis

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An epidural adhesion is composed of bands of scar tissue that form between the dura mater and surrounding tissue, causing them to stick together. One major cause of adhesion is surgical procedure of a herniated lumbar disc (HLD). Alkalay et al (1) reported that formation of dense scar tissue adjacent to the dura matter following surgical laminectomy and discectomy is a normal physiologic response to surgery. Furthermore, Ozer et al (2) reported that fibroblast migration causes fibrotic tissue to replace

normal epidural fat after lumbar spinal surgery, and Bosscher and Heavner (3) reported the prevalence of severe epidural fibrosis with persistent lower-back pain after lumbar surgery to be 83.3%. Epidural adhesion can also develop from nonsurgical stimuli. Mccarron et al (4) demonstrated that a herniated nucleus pulposus causes an inflammatory response in the epidural space. Therefore, a simple herniated lumbar disc can cause epidural adhesion in the absence of spinal surgery.

Although the relationship between epidural adhesion and radicular pain has been well documented (5-7), the underlying mechanism of spinal pain caused by epidural adhesion has not yet been elucidated. Therefore, lysis of epidural adhesions has been used to treat such spinal pain whether or not the patients undergo surgery. The purpose of this study is to elucidate the underlying mechanism of spinal pain generated by epidural adhesions and to enhance the perceptibility of mechanical analysis using a 2-dimensional (2D) nonlinear finite element (FE) analysis.

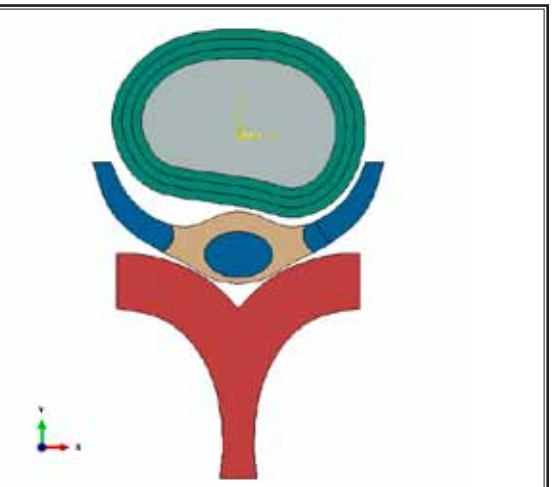

Fig. 1. *A 2D non-linear FE model consisting of the nucleus pulposus, annulus fibrosus, dura matter, cauda equina, spinal nerve, and lamina.*

Methods

Finite Element Model

To create a 2D model of the spine, computerized tomographic (CT) scans of a 24-year-old man with disc protrusion at the L4-5 disc level were used after obtaining informed consent. A 2D model of the spine was developed, consisting of intervertebral discs (nucleus pulposus and annulus fibrosis), dura mater, cauda equina, spinal nerves, and lamina. The FE mesh was analyzed with commercially available software (ABAQUS 6.13.; Hibbitt, Karlsson & Sorenson, Inc., Providence, RI, USA) (Fig. 1). The intervertebral disc was modeled as hyperelastic using the Mooney-Rivlin equation, and all the other structures were modeled as linear-elastic with their properties assigned as listed in Table 1. The Young's modulus of the dura mater and the lamina was 1 MPa and 10000 MPa, respectively (8,9). The number of element of dura mater was 597, lamina was 779, and intervertebral disc was 1610. To analyze the mechanical differences caused by epidural adhesion, 2 different models were created using the original and reciprocal contact conditions (adhesion model vs. control model).

Epidural Adhesion Setting

Modeling epidural adhesion between the dura mater and annulus fibrosis at a protrusion site was the core of this study. The contact surface between the dura and annulus fibrosis was modeled to be "rough" in the adhesion model. In this situation, no slip could occur once the 2 surfaces were in contact, resulting in a lack of adaptive displacement between the dura mater and annulus fibrosis. In the control model, the contact surface between the dura and annulus fibrosis was modeled to be "frictionless." In this case, slip can occur between the 2 surfaces, allowing for adaptive displacement between the dura mater and annulus fibrosis. We then simulated these 2 different models and analyzed the maximal compression force on the spinal nerve, especially in the dorsal root ganglion (DRG), and compared the magnitude of mid-line displacement of the cauda equina.

Table 1. *Material properties and elements used as constitutive parts of the model.*

Material	Model	Young modulus (MPa)	Poisson's ratio	Element type
Nucleus pulposus	Mooney-Rivlin	C10 = 0.12 C01 = 0.09 D1 = 1		
Annulus fibrosis	Mooney-Rivlin	C10 = 0.56 C01 = 0.14 D1 = 1		
Dura matter	Linear elastic	1	0.499	4-noded tetra*
Cauda equina	Linear elastic	40.96	0.37	
Spinal nerve	Linear elastic	40.96	0.37	
Lamina	Linear elastic	10000	0.2	

*A 4-node bilinear plane stress, quadrilateral, reduced integration, hourglass control

Analysis

Auto-simulation was conducted under 2 different conditions, rough contact and frictionless contact using the ABAQUS software. The node path was located along the surface between the annulus fibrosis and the dura meter to measure the stress value and displacement of the dura mater (Fig. 2). Von Mises stress was used to analyze the magnitude of compression force of protruded annulus fibrosis to the dura mater. To compare the values of Von Mises stress and displacement of dura mater, we analyzed the node path values with an independent t-test. Analysis was conducted with the PASW statistics 18 software program (PASW, IBM, USA). A $P < 0.05$ was considered statistically significant.

Results

Mid-line Displacement

In the adhesion model, there was no slip between annulus fibrosis and dura mater, leading to the conclusion that the protruded portion of the annulus fibrosis directly compressed the DRG area, and the mid-line of the cauda equina was minimally displaced to the contralateral side. The control model demonstrated adaptive contralateral displacement of the dura, resulting in lower compression by the protruded annulus fibrosis compared to that in the adhesion model (Fig. 3). Moreover, in the adhesion model, higher von Mises stress was noted in the spinal nerve, especially on the DRG (adhesion model 0.67 vs. control model 0.46). The average displacement value was significantly higher in the control model than the adhesion model (3.58 ± 0.34 vs. 2.59 ± 0.43, $P < 0.001$) (Table 2) (Fig. 4).

Von Mises Stress

To calculate the magnitude of compression force of the protruded annulus fibrosis to the dura mater, we used the node path with Von Mises stress. The nodes were located at the surface of the dura mater that was compressed by the protruded annulus fibrosis. A total

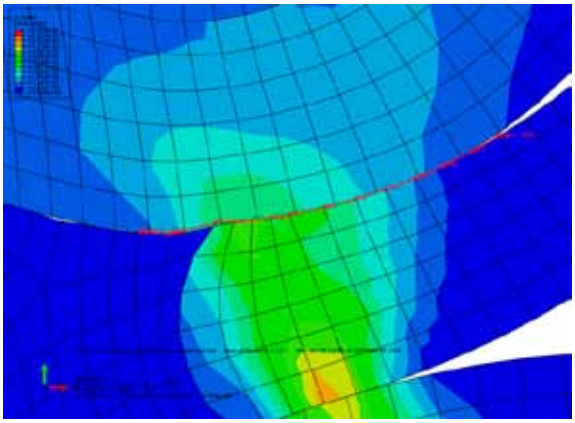

Fig. 2. *Node path (red dot and line) along the surface between the annulus fibrosus and dura mater. A total of 15 nodes were located from medial to lateral.*

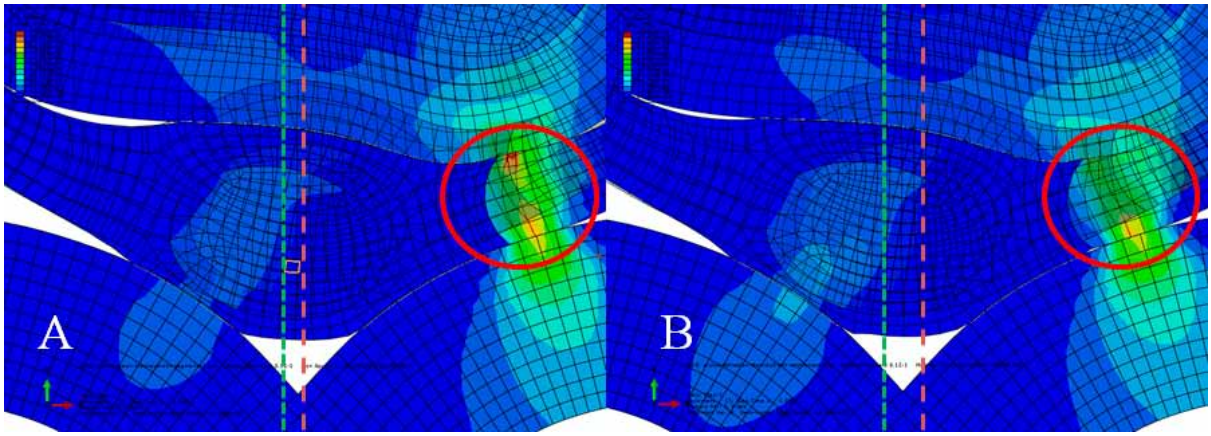

Fig. 3. *Comparison of midline displacement between the two models. A, Adhesion model. B, control model. Red dotted line indicates the midline of the lamina, green dotted line indicates the center of the cauda equina. Reddish color change can be seen in the DRG area in the adhesion model (red circle, panel A).*

Table 2. *Displacement of the dura mater along the node path.*

Node number	Adhesion	Control	*P* value
1	2.26	3.13	
2	2.21	3.31	
3	2.03	3.16	
4	2.17	3.26	
5	2.21	3.31	
6	2.32	3.38	
7	2.40	3.43	
8	2.55	3.56	
9	2.68	3.66	
10	2.83	3.77	
11	2.96	3.87	
12	3.10	3.98	
13	3.23	4.08	
14	3.37	4.18	
Mean ± SD	2.59 ± 0.43	3.58 ± 0.34	0.000

Independent t-test was performed. Node number, from medial (No. 1) to lateral (No. 14); SD, standard deviation

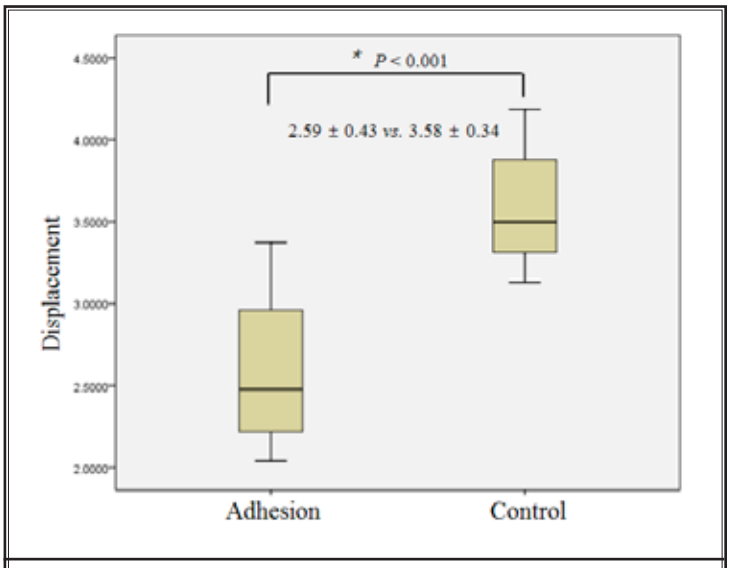

Fig. 4. *Comparison of midline displacement between the models.*

of 15 nodes were located along the distance medial of the DRG to lateral of the DRG (Fig. 2). Stress values were measured at all 15 nodes. In the adhesion model, the average stress value was 0.20 MPa, and the maximal value was 0.67 MPa. In the control model, the average stress value was 0.17 MPa, and maximal value was 0.46 MPa (Table 3). In addition, we confirmed that the shape of the stress distribution was narrow with a higher peak in the adhesion model, while that of the control model was wide with a lower peak (Fig. 5). However, this difference was not statistically significant.

Discussion

Our study showed that epidural adhesion leads to higher stress on the spinal nerve, especially the DRG. One of the most common causes of epidural adhesion is spine surgery, and the formation of epidural adhesion is the result of an invasion of hematoma by dense fibrotic tissue originating from the fibrous layer of the periosteum. This fibrous tissue is accumulated in the epidural space around the spinal nerve, resulting in compression stress (10-12). Previous studies have reported that persistent or recurrent pain caused by epidural adhesions has a relationship with surgical procedure of a herniated lumbar disc (13,14). This condition can increase the rate of revision surgery. Many animal studies have shown that epidural adhesion induces tethering of the spinal nerve. Kulkarni et al (15) and Dumania et al (16) used a rat model to demonstrate that laminectomy and disc-injury can produce substantial and quantifiable epidural fibrosis and tethering of the spinal nerve. Their study reported that the mechanical transformation around the spinal nerve induced post-laminectomy pain syndrome. However, most previous research focused on histological or anatomical aspects rather than mechanical forces.

Our study is the first to utilize FE modeling to analyze the mechanical transformation of the annulus fibrosis and the dura mater in the setting of epidural adhesion. Our FE model demonstrated how the compression force differently affects the spinal nerve and the DRG. Furthermore, stress values were measured at each portion of the DRG. This model also confirmed that, under normal conditions, without epidural adhesion, adaptive mild displacement of the dura mater and cauda equina occurs to reduce the compression force of a disc protruded to the contralateral side. Accordingly, we were able to identify the exact mechanism of epidural adhesion.

Epidural adhesion and fibrosis provoke spinal pain by inducing vascular abnormality and mechanical transformation. Histological examination of cadaveric herniated lumbar discs has been conducted, showing congestion and thrombosis of the local venous structures

with basement membrane thickening and endothelial fibrosis. Despite absence of direct nerve compression at these sites, epidural fibrosis and atrophy were frequently identified (17). This vascular abnormality can induce the obstruction of venous outflow and lead to ischemic damage to spinal nerves. Therefore, the presence of epidural adhesion can be a poor prognostic factor when determining the treatment for a patient with a herniated lumbar disc. Numerous experimental studies about prevention of post-laminectomy epidural adhesion have been published (12,18-20). They used various materials to prevent epidural adhesion and highlighted on its usefulness.

Epidural lysis of adhesion (ELOA) is a well-known procedure for addressing epidural adhesion. This procedure can be applied to treat not only post-laminectomy pain, but also epidural adhesion of other origin, for example, disc protrusion or spinal stenosis (21). Birkenmaier et al (22) reported that the ELOA procedure is effective and has a lavage effect to the adhesion site, reducing the local concentration of proinflammatory substances. Previous studies also posited that epidural neurolysis is an interventional pain management technique that is refractory to conventional treatment (23-27). Ansari et al (28) and Bosscher and Heavner (29) suggested that the peridural membrane is present in the spinal canal of humans and has a physiologic function, similar to the pleura, and inflammation or sensitization of it can produce spinal pain. Therefore, they insisted that mechanical destruction of the peridural membrane is effective for pain elimination (28,29). However, these studies reported only the clinical result of the procedure, not the mechanism of adhesiolysis. Our present study revealed the mechanism of severe pain development under epidural adhesion using an FE model. The higher stress on the spinal nerve seen with epidural adhesion can elicit more severe spinal pain under a similar magnitude of lumbar disc protrusion. Therefore, we believe that the ELOA procedure has the potential to decrease spinal pain in patients with herniated lumbar disc as well as those with post-spinal surgery syndrome.

There are some limitations in this study. The FE model used in this study is 2D non-linear, but the human intervertebral disc, dura matter, and lamina are 3D structures. Goto K et al (30) investigated mechanical analysis of lumbar vertebrae using a 3D FE model and reported its usefulness. Therefore, to demonstrate our

Table 3. *Von Mises stress on the dura mater around the DRG along the node path.*

Node number	Adhesion (MPa)	Control (MPa)	*P* value
1	0.037	0.020	
2	0.045	0.022	
3	0.055	0.025	
4	0.365	0.234	
5	†0.673	0.443	
6	0.658	†0.461	
7	0.420	0.289	
8	0.355	0.312	
9	0.176	0.299	
10	0.100	0.229	
11	0.055	0.172	
12	0.044	0.112	
13	0.030	0.038	
14	0.024	0.014	
15	0.019	0.006	
Mean ± SD	0.203 ± 0.232	0.178 ± 0.159	0.733

Independent t-test was performed. Von Mises stress value from medial (No. 1) to lateral (No. 15); SD, standard deviation; †, maximal value.

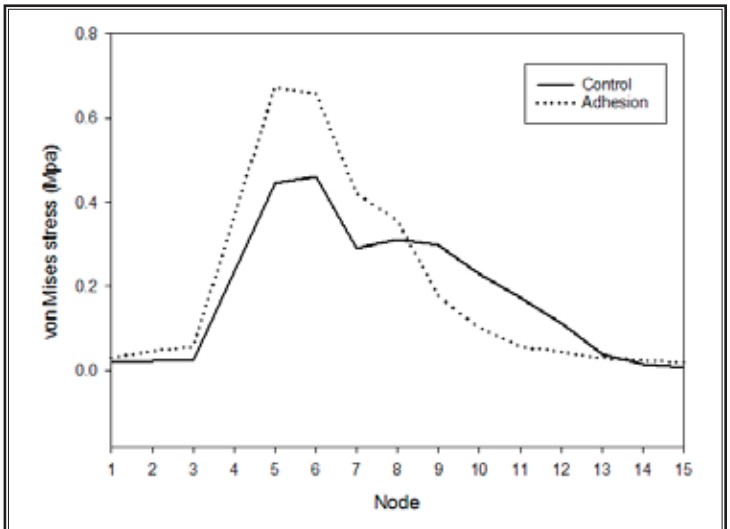

Fig. 5. *Distribution of stress along the node path. The adhesion model shows a narrower and higher peak than the control model.*

findings more precisely, we believe that 3D non-linear FE analysis would be beneficial. However, the 3D FE model of vertebra including the spinal cord, intervertebral disc, facet joint, ligaments, and dura matter is quite complex. Therefore, it will take more resources and effort to elucidate the mechanism of pain generation by epidural adhesion with complicated structures and various boundary conditions. The main character of the FE model is mathematical approximations of reality (31), and the main aim of this study was merely to elucidate the underlying mechanism of adhesion. Therefore, we believe that the 2D FE model was suitable in this study, as it greatly simplified the analysis. Furthermore, the validity of our 2D non-linear FE model of the intervertebral disc and dura mater needs to be investigated further. Despite the weaknesses, this study successfully demonstrated the mechanism of epidural adhesion. Further studies should focus on an effective strategy to achieve substantial lysis of epidural adhesion.

Conclusion

Epidural adhesion provokes substantial increase of stress to the spinal nerve, especially on the DRG. Increased stress on the DRG can elicit more pain under a similar magnitude of herniated lumbar disc.

Acknowledgments

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