Original article

Biomechanical effects of vertebroplasty on thoracolumbar burst fracture with transpedicular fixation: A finite element model analysis

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ABSTRACT

Objective: To investigate the biomechanical effects of augmentation of the fractured vertebrae after posterior instrumentation.
Methods: By simulating internal fixation plus augmentation with cement, eight tridimensional, anatomically detailed finite element models of the T11-L1 functional spinal junction were developed. Two kinds of models for mimicking different severity of the fracture were established according to the Denis’ classification. Augmentation with cement was conducted after reduction with posterior fixation using a universal spine system. These models assumed a three-column loading configuration as follows: compression, anteflexion, extension, lateroflexion and axial rotation. Stress of the implants and spine was evaluated.
Results: Data showed that for severely fractured models, augmentation apparently decreased the von Mises stresses by 50% for the rods and 40% for the screws, about 40% for the inferior endplate of T11, and 50% for the superior endplate of L1 in vertical compression and other load situations.
Conclusion: We should only apply vertebroplasty to prevent correction loss and implants failure based on the fact that it could significantly decrease stress of the instrumentations and spine when the vertebrae are severely fractured.
Level of evidence: Level IV, biomechanical study.

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1. Introduction

The thoracolumbar junction is susceptible to fracture and since 60% of these lesions are located between T11 to L2 [1]. Traumatic fracture of the spine is a serious medical condition, which can impose great impact on the quality of life of the patients [2]. Although different methods were described to solve the problem, no consensus has been reached until now. It is necessary, however, to surgically fix the fracture of thoracic or lumbar spine if axial or rotational stability is severely impaired or if a neurologic deficit is present. Short-segment pedicle screw instrumentation is an option widely used clinically to stabilize spine fractures; however, it does not offer support for the anterior-middle column [3]. Hardware failure and loss of reduction in long-term follow-up are recognized as complications caused this limitation [4]. Therefore, some researchers attempted to fill the fractured vertebral body with various grafts or substitutes as part of the surgical management of unstable thoracolumbar fractures.

Transpedicular spondiosaplasty was firstly developed and promoted by Daniaux to increase the stiffness of the anterior-middle column in which autologous bone grafts were impacted into the vertebral body through pedicles after reduction [5]. Recent researches have shown that this technique does not prevent the recurrence of kyphosis reliably and reproducibly [6]. For osteoporotic compression fractures, vertebroplasty was an effective treatment option [7–9]. Based on the positive outcomes, some authors combined the vertebroplasty with posterior instrumentation as an alternative to reduce complications and gained satisfying clinical outcomes. Cho et al. reported the efficacy of short-segment pedicle screw fixation augmented with PMMA in 20 patients suffering thoracolumbar fractures [10]. Marco et al. treated 28 patients who had burst fractures with posterior fixation and augmentation with calcium phosphate [11]. To date, however, few biomechanical studies have been performed to research the reasons why the augmentation in the fractured vertebral body can induce those complications.

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Table 1
The material properties of the finite element model.

<table>
<thead>
<tr>
<th>Component name</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson’s ratio</th>
<th>Cross-section area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cortical bone</td>
<td>12,000</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>100</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>Cartilage</td>
<td>10</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>Bony endplate</td>
<td>1000</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>Nucleus pulposus</td>
<td>1</td>
<td>0.499</td>
<td>–</td>
</tr>
<tr>
<td>Anulus fibrosus</td>
<td>450</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>ALL</td>
<td>20</td>
<td>0.3</td>
<td>63.7</td>
</tr>
<tr>
<td>PLL</td>
<td>20</td>
<td>0.3</td>
<td>20</td>
</tr>
<tr>
<td>LF</td>
<td>19.5</td>
<td>0.3</td>
<td>40</td>
</tr>
<tr>
<td>ISL</td>
<td>11.6</td>
<td>0.3</td>
<td>40</td>
</tr>
<tr>
<td>SSL</td>
<td>15</td>
<td>0.3</td>
<td>30</td>
</tr>
<tr>
<td>TL</td>
<td>58.7</td>
<td>0.3</td>
<td>3.6</td>
</tr>
<tr>
<td>CL</td>
<td>32.9</td>
<td>0.3</td>
<td>60</td>
</tr>
<tr>
<td>Cement</td>
<td>3000</td>
<td>0.41</td>
<td>–</td>
</tr>
<tr>
<td>USS</td>
<td>110,000</td>
<td>0.3</td>
<td>–</td>
</tr>
</tbody>
</table>


Therefore, the purpose of the current study was to clarify the true role what the vertebroplasty plays in treatment of the thoracolumbar fractures after the posterior short-segment fixation. We hypothesized that the argumentation from vertebroplasty played different roles in vertebrae with different extent of fracture.

2. Materials and methods

2.1. The construction and validation of normal T11-L1 FE model

The normal three-dimensional FE model of T11-L1 was developed from CT scanning of a cadaver using the Mimics software (version 10.01; Materialise, Inc., Leuven, Belgium). In the model, the vertebral body was assumed to have a cancellous core covered by a cortical shell. The nucleus pulposus occupied 43% of the total disc [12]. The mechanical effect of the cartilaginous endplate was negligible according to literature [13]. The element types of cortical bone, cancellous bone, bony endplate, facet joint cartilage, and nucleus pulposus were defined as solid elements with a material representation of linear isotropic elasticity or hyperelasticity. The element types of anterior longitudinal ligament (ALL), posterior longitudinal ligament (PLL), interspinous ligament (ISL), supraspinous ligament (SSL), capsular ligament (CL), ligamentum flavum (LF) and transverse ligaments (TL) enable tension deformation without compression behavior. The material properties [14–17] used in the current study were given in the Table 1. The validation of normal model was conducted according to published finite element model and human cadaveric thoracolumbar spines. The inferior endplate and spinous process of the L1 vertebra were fixed in all degrees of freedom. Pure moment of 7.5 Nm was applied on the superior endplate of T11 for validation.

2.2. The load models of fixation and augmentation

To mimic different extent of fracture of T12 vertebra, two kinds of model were constructed. For model one, the fracture was slight and only the superior 1/2 cancellous bone of the body was removed. For model two, the fracture was severe and both the superior 1/2 cancellous and cortical bone were removed. Some ligaments of PLL, LF, SSL, and ISL were removed at the level of the fractured vertebrae for both models. Two kinds of model were fixed as follows: fixation only with universal spine system (USS) (FO), fixation plus unilateral augmentation (FU), fixation plus bilateral augmentation (FB) and fixation plus middle augmentation (FM). The cement augmentation zone is consistent with views seen in post-operative CT axial scans and X-ray radiographs. One or two cement plugs were assumed and arranged symmetrically or unsymmetrically. It was assumed that the cement and bone elements were connected perfectly in the FE models. Eventually, we got eight different models for test (Figs. 1 and 2).

2.3. Boundary and loading conditions of FE models

Considering the effects of the paraspinal muscles as well as intra-abdominal pressure, all models were implemented with a 500 N [18,19] vertical compression load for a balanced standing; 500 N vertical compression load and 7.5 Nm moment were implemented for anteflexion, extension, lateroflexion and rotation at the same time. According to the spinal three-column concept, the load and moment were applied to the superior endplate and articular facets of T11, with 85% of these on the anterior-middle column and 15% on the posterior column [20,21]. All computational processes were performed with ABAQUS software (version 6.10; ABAQUS, Inc., Providence, RI, USA). The von Mises stresses of the instrumentations and the superior endplate of the L1 and inferior endplate of T11 were calculated to evaluate the effects of the cement augmentation.

2.4. Statistical analysis

SPSS 11.5 statistics software was used for t-test and P < 0.05 was defined as the statistical significance.

3. Results

3.1. Validation of the normal FE model

The ROMs predicted by my FE model of T11-L1 under flexion, extension, lateroflexion, and axial rotation were 7.8°, 5.5°, 8.1° and 2.6° which were similar to those published in literatures [22,23]. Highly stressed part was located at the upper posterior vertebral body. Furthermore, the L1 body had the highest stress concentration, which was in good agreement with the fact that more fractures happened in L1 [24]. For all vertebrae, the lowest stress in endplates were observed in these central part.

3.2. Stress of the implants for different FE models

The von Mises stresses of the instrumentations under vertical compression was shown on Fig. 3. For model one, augmentation with cement did not significantly lower down the von Mises stresses of instrumentations. On the contrary, for model two, augmentation apparently decreased the von Mises stresses by 50% for the rods and 40% for the screws. As to different kinds of augmentation, bilateral and middle cement had similar support, which was better than the unilateral cement. Similar changes could be seen in anteflexion, extension, lateroflexion and rotation.

3.3. The stress of the inferior endplate of T11 and superior endplate of L1

The von Mises stresses of the spine under vertical compression was shown on Fig. 4. Similarly, augmentation did not significantly change the stress of inferior endplate of T11 and superior endplate...
Fig. 1. A. CT scan of posterior short-segment fixation with vertebroplasty of a patient suffering fracture of T12. B. The plot of FE model fixed only with the universal spine system.

Fig. 2. The models of T11 ~ L1 burst fracture fixed with USS and augmentation with cement. A. Slightly fractured model: the superior 1/2 cancellous bone was removed. B. Severe fractured model: the superior 1/2 cancellous and cortical bone were removed. C ~ E. The augmented models with cement at unilateral, bilateral and middle zone.

of L1 for model one. On the contrary, for model two, augmentation apparently decreased the stress by about 40% for the inferior endplate of T11 and 50% for the superior endplate of L1.

Fig. 5 shown the nephogram of the superior endplate of L1 under vertical compression. Dark color such as blue means lower von Mises stresses while bright color stands higher von Mises stresses. We could figure out that severe fracture of T12 resulted in higher von Mises stresses focus on the superior posterior zone of the vertebral body for model two than that in model one. After augmentation, the von Mises stresses of the superior endplate of L1 did not significantly change for model one. For model two, however, augmentation apparently decreased the von Mises stresses. As to different kinds of augmentation, bilateral and middle cement had similar support, which was better than the unilateral cement. Similar changes could be seen in anteflexion, extension, lateroflexion, and rotation.

4. Discussion

Posterior stabilization is a widely accepted treatment for instability of the thoracic and lumbar spine. However, isolated posterior fixation is often associated with loss of correction or implant failure. According to the spine three-column theory, the anterior and middle columns play an important role in supporting the upper body.

Previous studies suggested that it was because of the intrusion of the disc into the weaken vertebral body through the fractured endplate resulting from insufficient support leaded to those complications [25,26]. It might be an effective method to reduce such complications by restoring the endplate anatomy after reduction and instrumentation. Vertebroplasty did make a great contribution to restore the strength and stiffness of the fractured vertebra when it was utilized independently. Hence, many surgeons thought that they would have the same function after posterior pedicle screw fixation. But, few researchers paid attention on its true biomechanics. We therefore conducted this study to clarify this issue.

Our current study focused the stress on the instrumentations and spine. Results from two kinds of models were apparently different because the superior 1/2 cortical bone of model two was removed to mimic the severe fracture. Without the support of the cortical, bone which bears the major weight of upper body, stress on the implants and superior posterior part of vertebral body sharply increased. Vertebroplasty after fixation could significantly lower down the stress compared to fixation only for severely fractured model which is consistent the biomechanical study conducted by Mermelstein et al. [27] in cadaveric L1 burst fracture model using short-segment pedicle screw instrumentation and reinforcement of L1 with hydroxyapatite cement. They found that transpedicular vertebral body reconstruction with hydroxyapatite cement reduced screw-bending moments by 59% in flexion and 38% in extension. Mean initial stiffness in the flexion-extension plane was increased by 40%.

However, vertebroplasty did not change the stress for slightly fractured model, by which we could draw a conclusion that vertebroplasty could not make enough contribution to decreasing stress concentration for non-severe fractures. Therefore, we should reevaluate our taken-for-granted perspective for the biomechanical augmentation in slight thoracolumbar fracture. Appling of bone substitutes in slight fracture maybe have other contribution to the bone healing, and then prevent complications. Bone substitutes such as calcium phosphate cement, calcium sulfate cement and something like that were widely applied in filling defects in bone. Basic researches demonstrated that they were biocompatible and osteoconductive. Giovanna et al. [28] filled the defects in rabbit models with calcium sulfate particles and found that calcium sulfate could promote newly bone formation. Study conducted by Kobayashi et al. [29] with ovine spines got similar result that calcium phosphate cements could be a good alternative for vertebroplasty.

Fig. 3. von Mises stresses of the instrumentations for different models.

Fig. 4. von Mises stresses of the inferior endplate of T11 and the superior endplate of L1 for different models.

Fig. 5. The nephogram of the superior endplate of L1.
Ligamentotaxis in posterior pedicle screw instrumentations indirectly reduces kyphotic deformity with relatively high failures [30]. Transpedicular augmentation techniques would help maintain the correction [10,31]. However, we should be cautious about the amount of cement in the severely fractured vertebrae with the risk of leakage and undesirable displacement of bone fragments, in which surgeon can’t achieve full reduction with persistent mild kyphosis. Therefore, we must carefully evaluate radiographies to know the extent of the fractured body before surgery, by which we could insert as much cement as possible to gain well result. For the mild kyphosis, we need more long-term observation of clinical application.

In our current study, eight finite element models of functional spinal unit T11-L1 were established on the basis of digital CT images. These virtual reality finite element models provided a powerful tool to investigate the biomechanics of the vertebraoplasty after posterior fixation. Nevertheless, some limitations of finite element method in this study must be considered. The assumptions of material representations of the biological structures such as linear isotropic elasticity were done for simplification. Our FE models are constructed from normal spine CT scans, which are different from patients whose spine existed kyphosis after fixation. Therefore, loads gained from literatures could be different from patients, which maybe influence the stress distributions on the instrumentations and spine. Besides, we only modeled two kinds of fracture, which are not always same to clinical cases. More kinds of different extent fractures of vertebra are needed to be developed and more appropriate boundary condition and loads should be set to further evaluate the function of the vertebraoplasty.

5. Conclusions

We should choose the vertebraoplasty in correct situations. When the vertebrae severely fractured, augmentation could significantly decrease stress of the instrumentations and spine, which could prevent correction loss and implants failure while vertebraoplasty does not make more contribution to reduce complications. We therefore should reevaluate our choice of this procedure.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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