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Biomechanical effects of cement distribution in the fractured area on osteoporotic vertebral compression fractures: a three-dimensional finite element analysis

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ABSTRACT

Background: According to some clinical studies, insufficient cement distribution (ID) in the fractured area and asymmetrical cement distribution around the fractured area were thought to be the reasons for unrelieved pain and recollapse after percutaneous vertebral augmentation (PVA) in the treatment of symptomatic osteoporotic vertebral compression fractures.

Methods: Finite element methods were used to investigate the biomechanical variance among three patterns of cement distribution (ID and sufficient cement distribution in the fractured area and asymmetrical cement distribution around the fractured area including upward [BU] and downward [BD] cement distribution).

Results: Compared with fractured vertebra before PVA, distribution of von Mises stress in the cancellous bone was transferred to be concentrated at the cancellous bone surrounding cement after PVA, whereas it was not changed in the cortical bone. Compared with sufficient cement distribution group, maximum von Mises stress in the cancellous bone and cortical bone and maximum displacement of augmented vertebra increased significantly in the ID group, whereas asymmetrical cement distribution around the fractured area in BU and BD groups mainly increased maximum von Mises stress in the cancellous bone significantly. Similar results could be seen in all loading conditions.

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Conclusions: ID in the fractured area may lead to unrelieved pain after PVA in the treatment of symptomatic osteoporotic vertebral compression fractures as maximum displacement of augmented vertebral body increased significantly. Both ID in the fractured area and asymmetrical cement distribution around the fractured area are more likely to induce recollapse of augmented vertebra because they increased maximum von Mises stress in the cancellous bone and cortical bone of augmented vertebra significantly.

1. Introduction

Osteoporotic vertebral compression fractures (OVCFs) are very common in the elderly, with an estimated 1.4 million new fractures occurring every year worldwide [1]. Until recently, symptomatic OVCFs were treated commonly with conservative methods including bed rest, analgesics, braces, and physical therapy. However, percutaneous vertebral augmentation (PVA), such as percutaneous vertebroplasty (PVP) and percutaneous kyphoplasty (PKP), has been introduced as an alternative treatment option [2,3]. Biomechanical studies showed significant increases in the stiffness and strength of individual-fractured vertebra after PVA [4,5]. Apart from rapid pain relief, another immediate effect of PVA was an increase of anterior vertebral height [6–8], which reduced kyphosis in patients [8]. The realigned spinal column and regained height in the augmented vertebra may decrease pulmonary and gastrointestinal complications and early morbidity related to compression fractures [9].

However, some studies reported that pain could not be relieved after PVA [10], and recollapse of the augmented vertebral bodies had been observed in some patients during the follow-ups [11,12]. Insufficient cement distribution (ID) in the fractured area was thought to be the reason for unrelieved pain, and asymmetrical cement distribution around the fractured area was assumed to be the main risk factor of recollapse of the augmented vertebral bodies [10–12]. To date, however, few biomechanical studies have been performed to research the reasons why ID in the fractured area and asymmetrical cement distribution around the fractured area can induce previously mentioned complications. Moreover, a better understanding of this biomechanical behavior is critical in optimizing the ultimate result of our treatment. The purpose of this study was to investigate biomechanical effects of ID in the fractured area and asymmetrical cement distribution around the fractured area on symptomatic OVCFs.

2. Materials and methods

2.1. The construction of normal and osteoporotic T11-L1 finite element model

A normal three-dimensional digital anatomic finite element (FE) model of T11-L1 was built using digitized image data of a T11-L1 motion segment. The image data of T11-L1 were obtained from a computed tomography (CT) scan of the thoracolumbar spine from a healthy volunteer who had no abnormal findings on roentgenograms and were taken at 1-mm intervals. The slice images were preserved in a computer and then imported to Mimics software (version 14.11; Materialise, Inc, Leuven, Belgium) for generation of the 3-dimensional FE model of T11-L1 vertebra, including cortical (1-mm-thick) and cancellous bone and posterior elements. The geometry of other structures (the annulus fibrosis, nucleus pulpous, facet cartilage, and end plate), which were difficult to separate from the CT images, were modeled using the solid modeling software, SolidWorks 2012 (SolidWorks Corp, Dassault Systemes, Concord, MA). The nucleus pulpous occupied 43% of the total disc [13]. The element types of cortical bone, cancellous bone, bony end plate, facet joint cartilage, annulus, and nucleus pulpous were defined as solid elements. Seven different ligaments including anterior longitudinal ligament, posterior longitudinal ligament, interspinous ligament, supraspinal ligament, capsular ligament, ligamentum flavum, and intertransverse ligaments in tension only were modeled with truss elements. These elements were orientated along the respective ligament directions obtained from anatomic textbooks. The assigned material properties were assumed to be linear, homogeneous, and isotropic. Tied contact interfaces were used to ensure the disc and ligament attachment to the vertebra and to prevent any relative movement during the simulations. Surface-based, finite-sliding contact with a friction coefficient 0.0026 was defined for facet joints. As a result, the model of the T11-L1 was developed, consisting of 147,355 solid elements, 388 truss elements, and a total of 235,594 nodes. The validation of the normal model was conducted according to the published FE model and human cadaveric thoracolumbar spines. The inferior end plate of L1 vertebra was fixed in all degrees of freedom. Pure moment of 7.5 Nm was applied on the superior end plate of T11 for validation.

Because vertebral compression fractures are related clinically to osteoporosis, a model of an osteoporotic T11-L1 was built. According to the methods reported by Polikeit *et al.* [14], a model with osteoporosis was defined as follows. The elastic moduli of all bony structures were reduced by 66% for the cancellous bone and by 33% for the cortical shell, the end plates, and the posterior elements. The other structures were left unchanged. The material properties of different components are listed in Table [14–17].

2.2. The simulation of compression fracture

Similar to simulation methods reported by Chiang *et al.* [18], the model was constructed with the following steps to simulate compression fracture on T12. The cleft was horizontally penetrated into the vertebral body by 20 mm through the center of the anterior cortical shell. The size of the cleft was approximately 20, 30, and 2 mm in depth, width, and height, respectively (Fig. 1A).