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Load shift of the intervertebral disc after a vertebroplasty: a finite-element study

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Abstract Infiltrating osteoporotic cancellous bone with bone cement (vertebroplasty) is a novel surgical procedure to stabilize and prevent osteoporotic vertebral fractures. Short-term clinical and biomechanical results are encouraging; however, so far no reports on long-term results have been published. Our clinical observations suggest that vertebroplasty may induce subsequent fractures in the vertebrae adjacent to the ones augmented. At this point, there is only a limited understanding of what causes these fractures. We have previously hypothesized that adjacent fractures may result from a shift in stiffness and load following rigid augmentation. The purpose of this study is to determine the load shift in a lumbar motion segment following vertebroplasty. A finite-element (FE) model of a lumbar motion segment (L4–L5) was used to quantify and compare the pre- and post-augmentation stiffness and loading (load shift) of the intervertebral (IV) disc adjacent to the

augmented vertebra in response to quasi-static compression. The results showed that the rigid cement augmentation underneath the endplates acted as an upright pillar that severely reduced the inward bulge of the endplates of the augmented vertebra. The bulge of the augmented endplate was reduced to 7% of its value before the augmentation, resulting in a stiffening of the IV joint by approximately 17%, and of the whole motion segment by approximately 11%. The IV pressure accordingly increased by approximately 19%, and the inward bulge of the endplate adjacent to the one augmented (L4 inferior) increased considerably, by approximately 17%. This increase of up to 17% in the inward bulge of the endplate adjacent to the one augmented may be the cause of the adjacent fractures.

Keywords Cement augmentation · Vertebroplasty · Complications · Adjacent fractures · Load shift · Finite-element modeling

Introduction

The mechanical properties of vertebral cancellous bone are a determinant of the mechanisms of load transfer within and between vertebral bodies. Age-related diseases, such as osteoporosis, weaken the cancellous bone and therefore affect the mechanism of load sharing between the vertebral cortex and cancellous bone. The vertebral cortex generally accounts for 45–75% of the load transferred throughout the vertebra, although this percentage increases with age [17].

As a result of the age-related changes, the incidence of osteoporotic vertebral fractures rises dramatically with age, particularly in the population over 80 years of age [16]. In the United States alone, osteoporosis is responsible for 1.5 million fractures annually, with 700,000 (47%) of these fractures being predominantly vertebral compression fractures (VCF) [16].

At present, the treatment of VCF consists of bed rest and pain medication. Surgical treatment of osteoporosis-induced spinal deformities is often difficult because conventional internal fixation systems fail to adequately an-

chor in osteopenic bone, resulting in a high complication rate. The current treatment options have been unsatisfactory.

Today, there is an option of using vertebroplasty for the augmentation of osteoporotic vertebrae. Mainly acrylic, but increasingly mineral, cements are used for this procedure. Vertebroplasty is increasingly being performed by spine surgeons and radiologists in Europe and North America [8, 11, 12, 14, 18].

Presently, the procedure is intended for patients with severe pain related to VCF. Prospective studies have indicated that vertebroplasty can achieve significant and rapid pain relief in 80–90% of patients [8, 11, 12]. The immediate pain relief following infiltration procedures strongly suggests a correlation between the procedure and pain relief. Prospective randomized studies are underway at several centers.

The gain in structural strength of the infiltrated vertebrae has been well documented through biomechanical tests [4, 5, 13, 21]. It is generally accepted that cement infiltration (filling the trabecular bone cavities with bone cement) (a) strengthens vertebrae to withstand a higher axial compressive force prior to fracture, and (b) stiffens the augmented vertebra beyond its initial stiffness. However, it is unclear what degree of stiffening and strengthening are required for an effective augmentation: that is, an augmentation that reduces adverse mechanical effects (e.g., adjacent fractures), yet offers long-term biomechanical stability.

The procedure's long-term safety and efficacy remain to be proven. Recent clinical and biomechanical evidence [6, 10] suggests that vertebroplasty may induce subsequent fractures in vertebrae adjacent to the ones augmented (Fig. 1). The cause of the adjacent fractures is as yet un-

clear. Previous knowledge of arthroplasty, however, suggests that an altered load transfer resulting from rigid fixation may induce degenerative changes in adjacent bone [2]. Thus, it is plausible that such a mechanism exists following a rigid cement augmentation, particularly because of the stiffness of bone cement compared to the stiffness of cancellous bone. We therefore hypothesized that filling vertebrae with bone cement may substantially alter their stiffness and induce a load shift across the IV disc, and that the resultant load shift may be the cause of adjacent fractures [3, 4].

To the authors' knowledge, there are no reports on the load shift of the adjacent intervertebral (IV) disc following a cement augmentation. The purpose of this paper is to quantify the subsequent load shift of an adjacent IV disc following a cement augmentation using the finite-element (FE) analysis of a lumbar motion segment. The ultimate goal is to help better understand the mechanism of adjacent fractures and therefore to reduce their prevalence.

Materials and methods

The present FE model, originally used and validated by Smit et al. [20] to investigate the mechanism of load transfer in vertebral cancellous bone, simulated a three-dimensional lumbar motion segment (L4–L5) with no posterior elements. The cortex (thickness = 1 mm) and endplates (thickness = 0.5 mm) of the L4 and L5 vertebrae were modeled as linear-elastic two-dimensional shells.

The material parameters of osteoporotic cancellous bone infiltrated with bone cement had already been determined in a previous independent study [3, 4]. Because of the small deformations trabecular bone undergoes, especially after the cement infiltration, a linear isotropic elastic model was considered to be sufficient for this application. The elastic parameters for the native osteoporotic bone were 81.57 ± 33.2 MPa. The bone–cement composite was up to 46 times stronger and up to 12 times stiffer than the native, non-injected bone.

In recent literature, the nucleus has often been modeled as a non-linear incompressible solid (Mooney-Rivlin), while the annulus was modeled as a linear-elastic solid [20]. The annulus was subdivided into a sequence of eight layers in which the elastic collagenous fibers were modeled using bar elements. The material parameters used in this study, which reflect the standard values of the literature [20], are listed in Table 1.

The IV disc was assumed to fill the space between the inferior L4 and superior L5 endplates. The nucleus occupied 43% of the total disc volume. In total, the model consisted of 2852 elements, with 6114 degrees of freedom. More details of this model are available in Smit et al. [20].

In a clinical procedure, surgeons tend to inject the maximum amount of cement possible, unless leakage is observed. The working hypothesis is that the more cement injected, the stronger and the better the reinforcement. To maximize the cement injection volume, Schildhauer et al. [18] applied suction to cadaveric vertebrae and reported a filling of up to 70% of the spinal body volume. To mimic an augmented vertebra, we assumed that one vertebra (L5) was entirely infiltrated with bone cement. The corresponding material parameters were taken from the experimental study. The FE models (pre- and post-injection) were subjected to the same quasi-static axial compression of 2.8 mm. The compression load increased in a linear fashion, in that the posterior endplate of L4 was displaced towards L5 in steps of approximately 0.2 mm. The

Fig. 1 The *left* image was captured immediately after multi-level augmentation. The *right* image (same patient) illustrates the damage (loss of height) of the adjacent (*highlighted*) vertebra after approximately 2 weeks

Table 1 Material parameters used in this study

Material	Elastic modulus (MPa)	Poisson's ratio (–)
Cortex bone	12,000	0.3
Endplates	12,000	0.3
Cancellous bone	81	0.2
Composite	972	0.2
Nucleus	$C_{01}=0.12, C_{02}=0.03$	–
Annulus ground	8	0.45
Annulus fibers, layers 1–2, 3–4, 5–6, 7–8	500, 485, 420, 360

Fig. 2 A comparison of stresses in a motion segment, showing the load shift that results from the rigid cement augmentation. The colors represent the mean stresses (MPa) in the sagittal plane in response to a quasi-static compression. In the non-augmented motion segment (*right*), the endplates bulge symmetrically (*green*) in response to nucleus hydrostatic pressure (*blue*), subjecting the adjacent cancellous bone to symmetric compressive stresses in the range of 1–1.5 MPa (*green*). In the augmented motion segment (*left*), the augmented cancellous bone of the L5 vertebral body (*lower*) acts as a pillar supporting the endplate. As a result, the forces are transmitted to cancellous bone by compression (*light green*), as opposed to the bending (bulge) in the non-augmented one. In response to the decreased bulge of the L5 superior endplate, the nucleus pressure increases (*blue*). As a result, the bulge of the inferior L4 endplate and the compressive stress in the L4 cancellous bone (*dark green*) increase by approximately 17%

inferior endplate of L5 was constrained along the longitudinal axis of L5.

The standard Lagrangian procedure within a commercially available package (MARC, MSC Software Corporation, Palo Alto, Calif.) was utilized for the treatment of the geometrical and physical nonlinearities of the present FE models.

Results

Confinement of the incompressible nucleus by the annulus gave the intervertebral disc considerable axial stiffness and produced a state of hydrostatic pressure, as shown in Fig. 2. The stiffness of the non-augmented motion segment was approximately 1580.7 N/mm. The compression of IV disc contributed as much as 64.7%, while the inward bulge of the superior L5 and inferior L4 endplates contributed as much as 35.3% to the axial compliance of the IV disc in the non-augmented motion segment. At the maximum load of 4.13 kN (corresponding to approximately 2.8 mm displacement of the superior L4 endplate relative to the fixed L5 inferior endplate), the superior L5 endplates deflected by up to 0.57 mm, while the adjacent L4 inferior endplate deflected by as much as 0.44 mm.

Augmenting L5 with bone cement stiffened the IV disc in axial loading by as much as 11.1%. The stiffness of the augmented motion segment was 1756.5 N/mm. As a result, the reaction force in the augmented motion segment

was approximately 495 N larger than in the non-augmented vertebra, when both models were subjected to an identical maximum compression of 2.8 mm.

The cement in the augmented vertebra underneath the L5 superior endplate acted as an upright pillar that considerably reduced its bulge, to approximately 0.04 mm (7% of that before augmentation). In contrast to the decrease in bulge of the superior L5 endplate, the bulge of the adjacent endplate (inferior L4) substantially increased, by as much as 17%. However, the bulge of both adjacent endplates of the augmented motion segment – if added together – was reduced to 0.56 mm (it was approximately 1 mm prior to augmentation). In contrast to the non-augmented motion segment, the axial bulge of both endplates of the IV disc only contributed up to 19.5% of the compliance of the intervertebral joint (it was 35.4% prior to augmentation). In other words, the decrease in the endplate bulges stiffens the IV disc by approximately 11.1%.

The hydrostatic pressure within the IV disc developed in a quasi-linear fashion with respect to the increasing compression (reaction forces). Because the axial reaction force in the augmented motion segment was larger than in the non-augmented one, the pressure increased accordingly. The maximum pressure in the augmented segment was approximately 0.75 MPa higher than in the non-augmented one. In relative terms, the maximum nucleus pressure in the augmented motion segment was approximately 19% higher than that in the non-augmented one.

Discussion

Bone cement can be effective at augmenting vertebrae. Recent clinical evidence suggests that vertebroplasty may induce subsequent fractures in adjacent vertebrae [6, 10]. The cause of these fractures is still unclear. We [3, 4] hypothesized that an altered load transfer across the IV disc space due to the cement filling may be the cause of these fractures. This study focused on determining the change in loading and stiffness that cement augmentation may induce in the IV disc adjacent to the augmented level.

The displacement-controlled FE model predicted that the endplate bulge of the augmented vertebra would be reduced by approximately 93%, consequently increasing the nuclear pressure of the adjacent IV disc by approximately 17%. In addition, a stiffening of the entire motion segment by approximately 11% and an increase in the adjacent endplate bulge of approximately 17% were predicted. In daily physical activities (e.g., walking), however, impact forces are most likely the determinant for the spinal axial compression, not vice versa. Therefore, one needs to evaluate the adjacent stresses before and after augmentation using a controlled force protocol (i.e., assuming that the axial forces before and after augmentation are identical). In the case of a controlled force simulation, the results were identical with respect to the reduced bulge and

the augmented vertebra (i.e., the endplate bulge of the augmented vertebra was reduced by approximately 93%, consequently stiffening the entire motion segment by approximately 11%). However, because the forces are the same in the augmented as in the non-augmented model, stresses and strains adjacent to the augmented vertebra did not differ substantially from those before augmentation. For example, the nucleus pressure of the adjacent IV disc and the axial bulge of the adjacent endplate was increased by only 3% compared to the non-augmented motion segment. This increase is probably too small to cause the adjacent fractures. A force increase may, however, result from the improved mobility following a vertebroplasty. It is conceivable that, because of the pain relief, the loading and motion patterns of patients change. However, these changes have not been investigated. The main effect that resulted from the FE simulation is that the IV disc adjacent to the augmented vertebra stiffens by approximately 17% because of the reduced endplate bulge after augmentation.

Cadaveric studies showed that the inward bulge of the endplates plays a major role in the mechanics of the IV joint. At small loads, the axial bulge of the endplate is small compared to the axial compression of the IV disc. However, at higher loads, the annulus fibers substantially stiffen the IV disc [9], and the contribution of the endplate bulge to the compliance of the IV joint becomes larger than the axial compression of the IV disc [7]. Without the endplate bulge, the radial bulge of the disc must increase considerably, which may damage the annulus fibers. Our FE model was not able to accurately predict the nonlinear interplay between the endplate bulge and the radial bulge of the disc with respect to the increased loading, but it has correctly predicted the functional stiffness of the IV joint and the average radial IV and endplate bulge. In a comparative study of augmented and non-augmented motion segments, Ferguson et al. [10] and Berlemann et al. [6] reported a decrease in ultimate failure load and displacement of 17.8% for vertebrae adjacent to a cement-infiltrated vertebra, but they also noted a trend toward a lower failure load with an increased degree of filling [6, 10]. These findings are interesting, since they show that there is no need to increase the force to cause adjacent fractures. Moreover, these studies [6, 10] showed that adjacent vertebrae fail under approximately 17% less force than non-augmented vertebrae. Our study suggested that the increase in deformations, especially the endplate bulge in the adjacent vertebra, results in higher adjacent stresses, which may be the cause of the fracture.

This present motion segment was only subjected to axial compression. In reality, the loading of a spinal motion is a combination of axial, bending, and shear loading. A motion segment is, however, most stable in axial loading because of the hydraulic confinement of the nucleus in the annulus. Therefore, the maximal stresses with a motion segment occur under axial loading. It should also be

noted that stability of the motion segment in the transverse directions is determined not by the vertebral body itself, but by the IV disc and the posterior elements. The transverse stability of a motion segment will most likely not change significantly due to a vertebroplasty, because the procedure only induces material changes in the augmented vertebra. Furthermore, the spinal posterior elements were not included in this FE model, mainly because their contributions to the load bearing in a motion segment under compression are small, with the external compression forces being primarily transmitted by the intervertebral disc [1, 15, 19].

At this point in time, cement augmentation is used mainly for palliative care, but it is becoming increasingly used for prophylactic treatments. In the case of a palliative treatment, the augmented vertebra may have a decreased height and adjacent intervertebral disc may be degenerated. These effects have not been taken into account in this model. Thus, the results of this study cannot be generalized, and further studies will be required to study these specific effects.

To our knowledge, no randomized studies have been published that show a higher incidence of adjacent fractures after a vertebroplasty than without a vertebroplasty. Thus, it is possible that adjacent fractures are the natural progression of osteoporosis, especially because adjacent vertebrae have similar mechanical and morphological properties. However, there is evidence from recent literature [6, 10] that the strength of adjacent vertebrae decreases

after a vertebroplasty, which indicates that load shift, as determined in this study, may also contribute to the risk of adjacent fracture.

Cement augmentation is effective at augmenting osteoporotic vertebrae. Clinical results are encouraging. Until now, there have been only a limited number of reports on the effects of cement augmentation on adjacent untreated structures [6, 10]. While cement augmentation significantly strengthens the infiltrated vertebrae, biomechanical and clinical evidence suggests that adjacent untreated vertebrae are weakened and may suffer fractures due to the altered load transfer in the spine following vertebroplasty. The exact mechanism of the fracture is still unclear.

Based on our results, we hypothesize that excess deformation in the adjacent endplate of up to 17.4% substantially contributes to subsequent adjacent fractures. In addition, we hypothesize that the use of polymers combining high strength, ductility and low stiffness will minimize the stiffness and load shift, and therefore decrease the risk of fracture following a vertebroplasty. To examine these hypotheses and to better understand the mechanical changes in the spine following a cement augmentation procedure, further biomechanical studies are planned to directly measure bone strains and endplate bulging before and after a cement augmentation procedure.

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References

- Adams MA, Hutton WC (1983) The effect of posture on the fluid content of lumbar intervertebral discs. *Spine* 8: 665–671
- Baroud G, Willmann G, Kreissig R (1997) The effect of the stem coating of the postoperative stress state of the femur. *Biomed Tech* 43:25–28
- Baroud G, Görke U, Beckman L, Steffen T (2001) Physical changes of the vertebral tissue treated with vertebroplasty. *Proceedings of the Eighteenth Congress of the International Society of Biomechanics (ISB)*, p. 728, 8–13 July, Zürich
- Baroud G, Nemes J, Ferguson SJ, Steffen T (2003) Material changes in osteoporotic human cancellous bone following infiltration with acrylic bone cement for a vertebral cement augmentation. *Comp Methods Biomech Biomed Eng* 6:133–139
- Belkoff SM, Mathis JM, Erbe EM, Fenton DC (2000) Biomechanical evaluation of a new bone cement for use in vertebroplasty. *Spine* 25:1061–1064
- Berlemann U, Ferguson SJ, Nolte LP, Heini PF (2002) Adjacent vertebral failure after vertebroplasty. A biomechanical investigation. *J Bone Joint Surg Br* 84:748–752
- Brinckmann P, Frobin W, Hierholzer E, Horst M (1983) Deformation of the vertebral end-plate under axial loading of the spine. *Spine* 8:851–856
- Cotten A, Boutry N, Cortet B et al (1998) Percutaneous vertebroplasty: state of the art. *Radiographics* 18: 311–320
- Eberlein R, Holzapfel GA, Suhulze-Bauer CAJ (1998) An anisotropic constitutive model for the annulus tissue and enhanced finite element analysis of intact lumbar disc bodies. *Comput Methods Biomech Biomed Eng* 4:209–230
- Ferguson S, Berlemann U, Heini PF, Nolte LP (2001) Evaluation of adjacent segment failure following vertebroplasty. *Proceedings of the 47th Annual Meeting, of the Orthopaedic Research Society (ORS)*, p. 280, San Francisco
- Galibert P, Deramond H, Rosat P, et al (1987) Preliminary note on the treatment of vertebral angioma by percutaneous acrylic vertebroplasty. *Neurochirurgie* 33:166–168
- Heini PF, Walchli B, Berlemann U (2000) Percutaneous transpedicular vertebroplasty with PMMA: operative technique and early results. A prospective study for the treatment of osteoporotic compression fractures. *Eur Spine J* 9:445–450
- Heini PF, Berlemann U, Kaufmann M, et al (2001) Augmentation of mechanical properties in osteoporotic vertebral bones—a biomechanical investigation of vertebroplasty efficacy with different bone cements. *Eur Spine J* 10:164–171
- Jensen ME, Evans AJ, Mathis JM, et al (1997) Percutaneous polymethylmethacrylate vertebroplasty in the treatment of osteoporotic vertebral body compression fractures: technical aspects. *AJNR* 18:1897–1904

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15. Nachemson AL (1963) The influence of spinal movement on the lumbar intradiscal pressure and on tensile stresses in annulus fibrosus. *Acta Orthop Scand* 33:183–207
 16. Riggs BL, Melton LJ (1995) The worldwide problem of osteoporosis: insights afforded by epidemiology. *Bone* 17[5 Suppl]: 505–511
 17. Rockoff SD, Sweet E, Bleustein J (1969) The relative contribution of trabecular and cortical bone to the strength of human lumbar vertebrae. *Calcif Tissue Res* 3:163–175
 18. Schildhauer TA, Bennett AP, Wright TM, et al (1999) Intravertebral body reconstruction with an injectable in situ-setting carbonated apatite: biomechanical evaluation of a minimally invasive technique. *J Orthop Res* 17:67–72
 19. Shirazi-Adl A, Drouin G (1987) Load-bearing role of facets in a lumbar segment under sagittal plane loadings. *J Biomech* 20:601–613
 20. Smit TH, Odgaard A, Schneider E (1997) Structure and function of vertebral trabecular bone. *Spine* 22:2823–2833
 21. Wilson DR, Myers ER, Mathis JM, et al (2000) Effect of augmentation on the mechanics of vertebral wedge fractures. *Spine* 25:158–165