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PII: S1529-9430(17)30038-4
DOI: http://dx.doi.org/doi: 10.1016/j.spinee.2017.01.013
Reference: SPINEE 57242

To appear in: *The Spine Journal*

Received date: 15-8-2016
Revised date: 21-12-2016
Accepted date: 30-1-2017

Please cite this article as: Jin Luo, Deborah J. Annesley-Williams, Michael A. Adams, Patricia Dolan, How are adjacent spinal levels affected by vertebral fracture, and by vertebroplasty? a biomechanical study on cadaveric spines, *The Spine Journal* (2017), http://dx.doi.org/doi: 10.1016/j.spinee.2017.01.013.

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How are adjacent spinal levels affected by vertebral fracture, and by vertebroplasty? A biomechanical study on cadaveric spines.

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Abstract

Background Context: Spinal injuries and surgery may have important effects at neighbouring spinal levels, but previous investigations of adjacent-level biomechanics have produced conflicting results. We use 'stress profilometry' and non-contact strain measurements to investigate thoroughly this long-standing problem.

Purpose: To determine how vertebral fracture and vertebroplasty affect compressive load-sharing and vertebral deformations at adjacent spinal levels.

Study Design: Mechanical experiments on cadaver spines.

Methods: 28 cadaveric spine specimens, comprising three thoracolumbar vertebrae and the intervening discs and ligaments, were dissected from 14 spines aged 67-92 yrs. A needle-mounted pressure transducer was used to measure the distribution of compressive stress across the antero-posterior diameter of both intervertebral discs. 'Stress profiles' were analysed to quantify intradiscal pressure (IDP), and concentrations of compressive stress in the anterior and posterior annulus. Summation of stresses over discrete areas yielded the compressive force acting on the anterior and posterior halves of each vertebral body, and the compressive force resisted by the neural arch. Creep deformations of fractured and adjacent vertebral bodies *under load* were measured using an optical MacReflex system. All measurements were repeated following compressive injury to one of the three vertebrae, and again after the injury had been treated by vertebroplasty. The study was funded by a grant from Action Medical Research, UK ($143,230). Authors of this study have no conflicts of interest to disclose.

Results: Injury usually involved endplate fracture, often combined with deformation of the anterior cortex, so that the affected vertebral body developed slight anterior wedging. Injury reduced IDP at the affected level, to an average 47% of pre-fracture values ($P<0.001$), and

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transferred compressive load-bearing from nucleus to annulus, and also from disc to neural arch. Similar but reduced effects were seen at adjacent (non-fractured) levels, where mean IDP was reduced to 73% of baseline values (P<0.001). Vertebroplasty partially reversed these changes, increasing mean IDP to 76% and 81% of baseline values at fractured and adjacent levels, respectively. Injury also increased creep deformation of the vertebral body under load, especially in the anterior region where a 14-fold increase was observed at the fractured level and a three-fold increase at the adjacent level. Vertebroplasty reversed these changes also, reducing deformation of the anterior vertebral body (compared to post-fracture values) by 62% at the fractured level, and by 52% at the adjacent level.

Conclusions: Vertebral fracture adversely affects compressive load-sharing and increases vertebral deformations at both fractured *and* adjacent levels. All effects can be partially reversed by vertebroplasty.

Keywords: Vertebral fracture; vertebral deformity; vertebroplasty; adjacent level; intradiscal pressure; cadaveric.

Classification: Basic science paper.

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Introduction

Injury and degeneration often affect more than one spinal level. 'Adjacent-level' pathology could be due to constitutional factors (such as genetic inheritance or ageing) leading to concurrent changes at several spinal levels. Alternatively, changes at one spinal level could have a direct biomechanical influence at adjacent levels, so that pathology spreads in a 'domino' effect, up or down the spine. This has important implications for the consequences of injury at one spinal level.

Adjacent level effects are equally important when assessing the impact of therapeutic interventions such as disc replacement,(1) spinal fusion and fixation,(2, 3) interspinous implants,(4) and techniques such as vertebroplasty(5) which augment fractured vertebrae with cement.(6-9) Approximately 50% of vertebral fractures that follow vertebroplasty affect an adjacent vertebra,(10-12) suggesting a 'domino' effect. On the other hand, vertebroplasty *reduces* the rate of adjacent-level fractures compared with conservative treatment,(9, 13) suggesting that constitutional factors are important.(14-16)

Experiments on living subjects show that sagittal-plane mobility (and bending stiffness) can be increased, decreased or remain the same at spinal levels that are adjacent to a fusion or to advanced disc degeneration.(17, 18) In-vitro experiments attempting to explain these effects also produce variable results which appear to depend on loading technique.(19) Changes in *compressive* load-sharing at adjacent levels have been studied less, possibly because it is more difficult to quantify than angular movements in bending. Vertebroplasty can reduce the failure strength of adjacent vertebrae if a large volume (7-11 ml) of cement is injected,(5, 20) presumably by increasing pressure in the adjoining disc nucleus(21) and increasing bulging of the adjacent endplate.(22) Other studies, however, report that vertebroplasty does not increase nucleus pressure right up to pre-fracture levels (23, 24) so that endplate deflection in

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adjacent vertebrae is not increased.(25) This disagreement may be attributable to differences in the volume and stiffness of bone cement used,(24, 26-30) with lower volumes of softer cement likely to reduce the risk to adjacent levels. Further investigations are needed to clarify the effects of fracture and surgical intervention on compressive load-sharing at adjacent levels.

To understand how compressive load is transferred through the spine, we developed and validated a technique for measuring compressive 'stress' across the mid-sagittal diameter of a loaded intervertebral disc, as shown in Figure 1A.(31, 32) Multiplying the average stress on each discrete region of the disc by the area of that region gives the compressive force on that region, and summing these small forces (**Figure 1**) yields the total compressive force exerted by the disc on the adjacent vertebral bodies. Subtracting this force from the applied compressive load then indicates the compressive force resisted by the neural arch.(33) These techniques have shown that vertebral body fracture transfers compressive loading from nucleus to annulus, and from disc to neural arch, and that these effects can be partially reversed by vertebroplasty.(24, 27, 34)

We have also developed a technique for assessing regional deformations of the vertebral body under load, using a MacReflex optical strain measurement technique. Both elastic and creep (time-dependent) deformations were greater anteriorly than posteriorly in older spines.(35, 36) Deformations were increased following vertebral fracture, and decreased following vertebroplasty.(37)

The present study will apply these techniques to answer the following questions. Does vertebral body fracture affect compressive load-sharing and deformation in adjacent vertebrae? And, does vertebroplasty make things worse, or better? Three-vertebra specimens were used so that close comparisons could be made between fractured and adjacent spinal levels in the same spine.

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Materials and methods

Experimental design Each cadaver spine was dissected to obtain a matched pair of specimens, each comprising three vertebrae and the intervening disc and ligaments. All specimens were compressed until one of its vertebrae fractured. Fractured vertebrae were treated by vertebroplasty, using either polymethylmethacrylate (PMMA) cement or an acrylic resin, with the upper specimen from each spine being alternately assigned to receive one treatment or the other. At each stage of the experiment (before fracture, after fracture and following vertebroplasty) specimens were subjected to 1 hr of compressive loading during which deformations of the vertebral bodies were evaluated optically. Intervertebral disc stress distributions, and vertebral wedging, were measured before and after fracture, after vertebroplasty, and following the final period of compressive loading which allowed consolidation of the augmented vertebral body. Measurements were compared between each stage of the experiment, and between the matched pair of specimens from each spine.

Cadaveric material Thoracolumbar spines (10 male, 4 female) were obtained from cadavers aged 67-92 (mean 80) yrs which were donated for medical research. After storage at -20˚C, each spine was thawed at 3˚C and dissected into two specimens comprising three vertebrae with the intervening discs and ligaments. The 28 specimens ranged between T8-T10 and L2-L4 (**Table 1**). Choice of spinal level was determined by the need to avoid large osteophytes (which interfere with disc stress measurements) and to maximize the use of scarce human tissue. Before testing, the bone mineral content (BMC) of each vertebral body was assessed using dual energy X-ray absorptiometry.(27). After testing, vertebral bodies were dissected and their volume measured by water displacement, for calculation of volumetric bone mineral density (BMD). Each intervertebral disc was sectioned in the transverse plane and graded for

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degeneration, using points 1 (non-degenerated) to 4 (severely degenerated) on a scale defined previously.(38)

Mechanical testing apparatus Specimens were secured in cups of dental plaster and loaded on a hydraulic materials testing machine (Dartec-Zwick-Roell, Leominster, UK). Low-friction rollers of equal height were used to apply pure compression to specimens in a neutral position (**Figure 2A).** This "neutral" position represents the natural angulation of the spinal segment when no external forces are applied to it. By altering the height of the rollers **(Figure 2B),** compression was also applied with each specimen flexed or extended relative to its neutral position by angles that are typical of those seen in flexed and lordotic postures in-vivo.(27)

Vertebral fracture Each specimen was positioned in moderate flexion to simulate a stooped posture in life. Flexion angles ranged from 4° at thoracic levels to 10° at lower lumbar levels to reflect natural variations in spinal flexibility. Specimens were then compressed at 3mm/s until the load-deformation graph, recorded in real-time, indicated that the elastic limit had been reached. This was marked by a reduction in gradient (stiffness). As soon as this occurred, the compressive load was removed so that fracture severity would be slight, and similar in all specimens. The force at the elastic limit was then recorded as the specimen's compressive strength. The location of fracture was confirmed from radiographs taken before and after damage, and from dissection.

Vertebroplasty One of each pair of three-vertebra specimens was injected with PMMA cement (Spineplex®, Stryker Instruments, Howmedica International, Limerick, Ireland) and the other with an acrylic resin (Cortoss®, Orthovita, Malvern, PA, USA) as described previously.(27) These cements differ in their material properties with PMMA having an elastic modulus of approximately 2.26 GPa compared with 5.51 GPa for Cortoss.(39) Total injected volume (through both pedicles) was 3.5 ml at spinal levels T7-T12, and 4 ml at L1-

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L5, which is sufficient to largely restore normal stress distributions on fractured vertebral bodies.(24) After injection, catheters and needles were removed from the vertebra, and the cement was left to set for 1 hr. This was followed by a 1 hr period of compressive loading at 1 kN to encourage cement consolidation.

Compressive stiffness With each specimen positioned in slight flexion (4°), the compressive force was increased at 500 N/s up to 1.0 kN, and then reduced to 50N. Compressive stiffness of the three-vertebra specimen was measured (at each stage of the experiment) as the slope of the load-deformation curve at 0.8 kN.

Stress profilometry and compressive load-sharing A miniature pressure transducer (Gaeltec, Dunvegan, Scotland), side-mounted in a 1.3 mm diameter needle, was used to measure the distribution of compressive "stress" along the mid-sagittal diameter of each intervertebral disc (**Figure 1A**), while the specimen was compressed by 1.0 kN (20 specimens), 0.75 kN (5 specimens) or 0.5 kN (3 specimens), depending on its size and BMD. The pressure transducer was attached to a linear variable displacement transducer (LVDT) which indicated the position of the transducer within the disc. Readings from the LVDT were recorded simultaneously with the pressure readings so that pressure could be plotted against distance across the disc to produce a "stress profile" (**Figure 1A**). Stress profiles were recorded at each stage of the experiment with the specimen positioned in slight extension (2°) to simulate the 'erect' standing posture,(40) and again in 4° - 6° of flexion (depending on specimen mobility) to simulate moderate flexion during light manual work.(41)

Stress profiles indicated the average intradiscal pressure (IDP) in the nucleus, and the size of stress 'peaks' (concentrations) in the anterior (SP_A) and posterior (SP_P) annulus (**Figure 1A**). Compressive load-bearing by anterior (F_A) and posterior (F_P) halves of the vertebral body were determined by summing forces over discrete areas (**Figure 1B**). Compressive loading of

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the neural arch (F_N) was then calculated by subtracting F_A and F_P from the applied compressive force.(33)

Vertebral body deformations Prior to fracture, specimens were subjected to 1hr of compressive loading at 1.0 kN to reduce intervertebral disc water content and height to physiological levels (42) and to enable deformation of the intact vertebral bodies to be evaluated.(35) The latter was assessed using a 2-D optical strain measurement system (MacReflex, Qualisys Ltd., Goteborg, Sweden) that tracked the position of six reflective markers attached to each vertebral body, at 50 Hz (**Figure 2**). Changes in the position of these markers during sustained loading enabled vertical deformations of the anterior, middle and posterior regions of the vertebral body to be assessed to an accuracy of 10μm.(43) The present paper will consider only the relatively large "creep" deformations, which were determined by subtracting the initial "elastic" deformation during application of the load from the total vertical deformation over the 1 hr loading period.(44) Creep deformations were measured before and after fracture, and again after vertebroplasty.

Vertebral wedging Specimens were loaded at 1kN in the neutral (erect) position while the position of reflective markers attached to the vertebral body was determined using the MacReflex (**Figure 2**). The vertical separation of markers placed on the anterior and posterior vertebral body was used to calculate anterior and posterior vertebral height and hence vertebral wedging. Changes in anterior and posterior vertebral body height, at each stage of the experiment, were used to calculate residual anterior wedging of the vertebral body, which is indicative of structural failure.(45, 46)

Statistical analysis BMD and degree of disc degeneration were compared in specimens in the two cement groups using matched-pair t-tests. The effect of disc degeneration grade on fracture type was examined using Fisher's Exact test. Repeated measures analysis of variance (ANOVA) was used to compare measurements following each intervention, with

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'cement group' as a between-subject factor. Analyses were performed separately for fractured and adjacent levels. Where a significant main effect was found, post-hoc paired comparisons were used to identify where differences arose. Significance was accepted at $P < 0.05$. SPSS v21.0 ® was used for statistical analysis.

Results

Specimen details These are summarised in **Table 1**. BMD ranged between 0.075 and 0.298 g/cm^3. Disc degeneration grades were between 2 and 4 and never varied by more than one grade point within an individual three-vertebra specimen. BMD and disc degeneration did not differ significantly between the two cement groups. In the case of disc degeneration, this was true when both average degeneration scores for each specimen and individual scores for each disc were compared.

Vertebral fracture Radiographs revealed, in 17/28 specimens, that fracture occurred in the uppermost (4/17) or lowermost (13/17) vertebra (**Figure 2A**), leaving two consecutive vertebrae intact. The vertebra next to the fractured vertebra was designated an 'adjacent vertebra' and the disc in between the two intact vertebrae was designated an 'adjacent disc'. The other disc (next to the fractured vertebra) was designated an 'affected disc'. In 10 specimens, fracture occurred in the middle vertebra (**Figure 2B**) so both discs were 'affected' and both vertebrae were 'adjacent'. In the remaining specimen, both the middle and lower vertebrae were damaged, so both discs were 'affected' and the upper vertebra was 'adjacent'. Consequently, a total of 29 vertebrae were fractured. Inspection of the radiographs, and subsequent dissection, showed that 8/29 fractured vertebrae showed damage to the endplate only, 9 suffered damage to the anterior cortex only, and 12 showed signs of damage to both the anterior cortex and endplate (**Table 1, Figure 3B**). The type of fracture appeared to be

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influenced by the degeneration grade of the adjacent disc (P=0.05) as follows: of 12 vertebrae that sustained a fracture of both the endplate and anterior cortex, 8 were adjacent to grade 3 discs and none were adjacent to grade 4 discs; in contrast, fractures adjacent to grade 4 discs always involved the anterior cortex only and not the endplate. In specimens where the degeneration grade varied between the two discs, fracture occurred adjacent to the more degenerated disc in 6 of these 7 cases.

Vertebroplasty Vertebroplasty was successfully completed in all specimens. Cement leakage was observed in one specimen which received PMMA (**Table 1**).

Compressive strength and stiffness Vertebral compressive strength varied between 1.3 and 5.5 kN (**Table 1**). Fracture reduced compressive stiffness of the three-vertebra specimen to 62 (STD 19)% of the baseline (pre-fracture) value ($P<0.001$). Vertebroplasty increased stiffness to 69 (STD 19)%, ($P<0.05$) but this remained lower than baseline ($P<0.05$). Specimens in the two cement groups had similar strength and stiffness (**Table 1)**.

Stress profilometry and compressive load-sharing Stress profile variables are summarised in **Table 2**, which also indicates the statistical significance of observed changes. Transducer damage during two tests meant that results could be analysed for only 36 'affected' and 16 'adjacent' discs. Cement type had no significant effect on stress profile results, so data from both cement groups has been pooled for conciseness.

Comparisons of average values in **Table 2** show that vertebral fracture reduced IDP in affected discs to 47% of baseline (in erect posture), and to 69% of baseline (in flexion). For adjacent discs, the changes were less, with IDP falling to 73% and 88% of baseline, respectively. Load-bearing by the anterior half of the vertebral body (F_A) of affected discs also decreased after fracture, to 75% of baseline in erect posture, and to 74% in flexion. Similar falls were seen in adjacent discs, with F_A decreasing to 75% and 64% of baseline in

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erect and flexed postures respectively. Load-bearing by the posterior half of the vertebral body (F_P) was little changed by fracture, in either affected or adjacent discs. The largest changes were seen in the neural arch, where compressive load-bearing (F_N) increased after fracture, to 134% of baseline in erect posture, and to 201% in flexed. Adjacent levels were affected by a similar amount, with (F_N) increasing to 160% and 185% of baseline in erect and flexed postures, respectively. Stress peaks in the annulus were very variable (**Table 2**), but fracture increased them significantly in the posterior annulus (SP_P), regardless of posture, and marginally decreased them in the anterior annulus (SP_A) in flexed posture. Similar but non-significant changes in stress peaks occurred in adjacent discs.

Vertebroplasty partially reversed the fracture-induced reductions in IDP and F_A at the affected level, usually raising them to within 70-90% of baseline values (**Table 2**). Vertebroplasty also reduced stress peaks in the posterior annulus (SP_P) back towards baseline, but had little effect on neural arch load bearing (F_N), which remained elevated. Some of the effects of vertebroplasty were evident at the adjacent level (especially F_A) but to a reduced extent. Consequently, changes at the adjacent level were not significant compared to post-fracture values although they were sufficient to restore some measures to pre-fracture values (**Table 2**). **Figure 4** compares the influence of fracture and vertebroplasty on IDP and F_A, at affected and adjacent levels.

Vertebral body deformations Regional measures of creep deformation in the vertebral body are shown in **Figure 5**. Cement type had no significant effect on these results so data from both groups has been pooled. Before fracture, creep deformation was generally more marked anteriorly when compared to middle and posterior regions, especially in the vertebral body which subsequently fractured. Following fracture, creep deformation of the fractured vertebral body increased significantly in all three regions, and these changes were fully or partially reversed following vertebroplasty (**Figure 5**). Changes at adjacent levels, although

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less marked, reflected those observed at the fractured level with values in middle and anterior regions being fully restored to pre-fracture values following vertebroplasty.

Vertebral wedging MacReflex data showed that vertebral fracture increased anterior wedging of the affected vertebral body ($P<0.05$) from 0.33^o (STD 0.47) to 0.94^o (STD 0.92). Wedging did not change significantly at 'adjacent' levels. Following vertebroplasty, anterior wedging of the fractured vertebral body decreased marginally, from 0.94^o to 0.78^o ($P>0.05$) and this value remained unchanged following the final period of creep loading. Cement type had no significant influence on these results.

Discussion

Summary of findings Compressive overload often damaged the anterior cortex as well as the endplate, increasing anterior wedging of the vertebral body. These injuries reduced nucleus pressure (IDP) and loading of the anterior vertebral body (F_A) at the injured level. In contrast, stress concentrations in the posterior annulus (SP_P) and loading of the neural arch (F_N) were substantially increased. Vertebroplasty partially reversed the changes in IDP, F_A and SP_P, and in vertebral wedging, but had little effect on F_N. Changes at the adjacent level were similar to those at the fractured level, but were reduced in magnitude, as indicated in **Figure 6.** Fracture significantly increased vertebral body deformation at both fractured and adjacent levels, and these changes were partially or fully reversed following vertebroplasty.

Strengths and weaknesses of the study A major strength is that complex loading was applied to large human specimens, so that loading of the vertebral bodies by adjacent discs was closely physiological. Consequently, induced vertebral fractures resembled those that occur in living people,(47) involving damage to both the endplate and anterior cortex.(48) The use of three-vertebra specimens also allowed compressive load distributions to be compared between fractured and adjacent vertebrae in the same cadaveric spines. "Stress profilometry"

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(49-51) and “stress integration” (33) have been extensively validated, and enable compressive load-sharing to be quantified between nucleus and annulus, as well as between disc and neural arch. Weaknesses of the study include the use of freeze-thawed cadaveric tissues which are unsupported by spinal musculature. However, death and frozen storage have little effect on the spine’s mechanical properties,(52, 53) and the loading apparatus was designed to reproduce the combined action of gravity and stabilising muscle forces (54) in a manner that prevents the spine ‘jack-knifing’ about the induced injury. Cadaveric studies are also limited to evaluating short-term effects, raising the possibility that fracture-induced changes may eventually be reversed. However, our previous cadaveric studies on osteoporotic spines show that vertebral deformity does not reverse after fracture if the spine is loaded. On the contrary, a small fracture-induced deformity progresses inexorably under load by a combination of consolidation and accelerated ‘creep’ mechanisms.(43) Vertebroplasty can reduce, but not eliminate, this progressive deformation.(37)

Relationship to previous work Endplate fracture is known to decompress the disc nucleus,(55) increase load-bearing by the neural arch,(27, 56) and lead to anterior wedging of the vertebral body.(48) Likewise, vertebroplasty partially reverses these changes,(24, 34) regardless of cement type(27) or volume.(24) The novelty of the present study is that changes observed at the injured level were mostly repeated (to a reduced extent) at adjacent (uninjured) levels.

Vertebral fracture has been reported to increase compressive strain in the anterior cortex of adjacent vertebrae,(57, 58). Current results support these findings, with adjacent vertebrae showing a 3-fold increase in creep deformation anteriorly (**Figure 5**). These increases occur even though the proportion of the applied compressive load acting on the anterior half of the adjacent disc is reduced (**Table 2**), suggesting that an increased proportion of the load is transferred from trabecular bone to the cortex, at both fractured and adjacent levels.

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Alternatively, it is possible that damage at the fractured level was accompanied by undetected microdamage at neighbouring levels, which caused them to deform more under load.

In the present study, only 3.5-4 ml of cement were used in vertebroplasty, because large cement volumes increase the risk of cement leakage(59) and may increase the risk of adjacent level fracture without contributing to pain relief.(60) Small cement volumes may explain why vertebroplasty did little to reduce neural arch load-bearing (**Table 2**). Previously, 7ml of cement was shown to substantially unload the neural arch and restore the spine's compressive stiffness.(24) For comparison, the volume of thoracolumbar vertebral bodies is approximately 15-35ml.(61)

Explanation of results Vertebral fracture often damages an endplate, allowing it to deform more so that the disc nucleus is decompressed.(55) In older spines, the anterior cortex also becomes susceptible to fracture because of osteoporotic changes which accompany disc degeneration.(62) When discs are severely degenerated, the anterior vertebral body appears to be the most likely site of fracture presumably because intradiscal pressure is too low to fracture the endplate. Once damage occurs, some compressive load-bearing is shifted to the annulus, and hence to the vertebral cortex and this may contribute to increased deformations of the vertebral body, especially in the anterior cortex which is often damaged as a result of compressive overload. Increased loading of the annulus causes it to bulge radially and lose height, increasing compressive load-bearing by the neural arch. Anterior vertebral collapse also shifts load-bearing from anterior to posterior, so that loading of the anterior vertebral body (F_A) decreases while stress concentrations in the posterior annulus (SP_P) increase. Increased neural arch load-bearing is substantially transmitted to adjacent levels via the apophyseal joints, whose articular surfaces have only a thin covering of compliant cartilage to separate adjacent bones. Changes in intra-discal stresses are also transmitted to adjacent levels, but the effect is reduced by the relative deformability of intervertebral discs compared

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to the bony apophyseal joints, which makes the anterior column much more compliant (**Figure 4**). Vertebroplasty supports the damaged endplate and anterior cortex with injected cement, reducing their deformation and hence reversing the above changes.

Overall, the results of this study support the concept of injury at one spinal level having a direct biomechanical influence at adjacent levels, so that pathology spreads in a 'domino' effect. However, the results do not rule out the possibility that biological predisposition (via genetic inheritance or ageing) can also promote degenerative changes at several spinal levels.

Clinical significance Vertebral body fracture shifts compressive load-bearing to the 'posterior column' of neural arches, and a similar but reduced shift occurs at adjacent levels. This will cause stress-shielding and (eventually) weakening of the anterior column of these neighbouring vertebrae.(62, 63) Therefore, the results of this study can explain why vertebral fracture increases the risk of subsequent fracture at adjacent levels.(14, 16, 64, 65) The fact that vertebroplasty partially reverses this shift in load-bearing and also reduces vertebral body deformation under load at both damaged *and* adjacent levels, suggests that the procedure is beneficial rather than harmful to adjacent vertebrae. We found no evidence that injecting 3.5-4 ml of cement increases disc stresses above baseline, at either the injured or adjacent levels, in line with previous work.(23, 24, 27, 34) This could explain why patients treated with vertebroplasty have a lower rate of adjacent level fracture compared with conservative treatment.(9, 13)

Unanswered questions and future research Kyphoplasty (a modification of vertebroplasty) is more effective at restoring vertebral body height and shape following fracture.(66) Future research should examine whether kyphoplasty also has beneficial effects at adjacent spinal levels.

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Acknowledgements: We thank Clare Costigan for technical assistance. The study was funded by a grant from Action Medical Research, U.K. Vertebroplasty materials and equipment were provided by Orthovita and Stryker U.K.

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Figure 1. (A) Typical 'stress profile' indicating the intradiscal pressure (IDP), and the peak compressive stress in the anterior (SP_A) and posterior (SP_P) annulus. **(B)** To calculate the total compressive force acting on the disc from the stress profile, anterior and posterior halves of the disc were each modelled as a series of semi-elliptical strips of known area. The compressive force acting on the N^{th} anterior strip (F_{AN}) was quantified by multiplying its area (S_N) by the average stress on this strip (P_{AN}) taken from the stress profile. The same procedure was carried out for all posterior and anterior strips. These individual small forces were summed to give the compressive force acting on the anterior (F_A) and posterior (F_P) halves of the disc. The compressive force acting on the neural arch (F_N) was then obtained by subtracting F_A and F_P from the known force applied to the specimen. Adapted from Pollintine et al. (33).

Figure 2. Each three-vertebra specimen was secured in cups of dental plaster and compressed by two low-friction rollers, the height of which could be altered to simulate "neutral" postures, where no bending was applied (A), or "flexed" postures (B). If fracture was induced in the lowest vertebra (X), and the other two were unfractured (U), then the disc between the middle and lowest vertebrae was designated the 'affected' disc, and the disc between the two upper vertebrae was termed 'adjacent', as depicted in (A). Equivalent terminology was used if the uppermost vertebra was fractured. If the middle vertebra was fractured, then both discs were considered to be 'affected' as depicted in (B).

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Figure 3. Radiographs of a cadaveric specimen (Male, 92 yrs, T11-L1) taken before (A) and after (B) fracture. The block arrow indicates where the main fracture plane meets the anterior cortex.

Figure 4. Effects of vertebral fracture and vertebroplasty on 'affected' and 'adjacent' discs. A) Nucleus pressure (IDP) decreases following vertebral fracture, and increases following vertebroplasty, at both affected and adjacent levels. Data refers to erect posture. B) Loading of the anterior vertebral body (FA), expressed as a percent of the total applied load, decreases following vertebral fracture, and increases following vertebroplasty, at both affected and adjacent levels. Data refer to flexed posture. Significant differences between pre- and post-fracture values are denoted * (P<0.05), ** (P<0.01) and *** (P<0.001). Significant differences between post-fracture and either post-vertebroplasty or post-consolidation values are denoted + (P<0.05), ++ (P<0.001) and +++ (P<0.001). Error bars indicate the SEM.

Figure 5. Vertebral fracture and vertebroplasty affect creep deformation of fractured and adjacent vertebral bodies. Measurements were made pre-fracture (Pre_X), post-fracture (Post_X) and post-vertebroplasty (Post_VP) in the posterior, middle and anterior cortex of each vertebral body. Significant differences between pre- and post-fracture values are denoted * (P<0.05), ** (P<0.01) and *** (P<0.001). Significant differences between post-fracture and post-vertebroplasty values are denoted † (P<0.05), †† (P<0.001) and ††† (P<0.001). Error bars indicate the SEM.

Figure 6. Cartoon illustrating how vertebral fracture alters compressive load-sharing at the fractured and adjacent levels. As indicated by the size of the arrows, fracture transfers loading from the central vertebral body to the vertebral cortex, and to the neural arch. The adjacent level is similarly affected, but to a reduced extent. Vertebroplasty partially reverses these changes. Note that vertebral fracture increased anterior wedging of the vertebral body by only 0.61 degrees on average.

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Table 1. Details of the 14 pairs of specimens tested

Spine	Gender	Age (years)	Spinal level		Disc Degeneration#		BMD (g/cm^3) $^+$		Yield strength (kN)		Compressive stiffness (kN/mm)		Fracture type	
			C	P	C (U:L)	P (U:L)	C	P	C	P	C	P	C	P
1	Female	87	T9-T11	T12-L2	4:4	3:3	0.075	0.077	1.5	1.5	1.60	0.42	AC	EP
2	Male	90	T10-T12	L2-L4	3:3	3:2	0.086	0.129	1.5	1.9	0.82	0.87	EP+AC	EP+AC
3	Male	79	L2-L4	T11-L1	2:2	3:3	0.298	0.270	4.7	5.5	1.49	2.57	EP	EP
4	Male	71	T11-L1	T8-T10	2:3	3:3	0.270	0.172	2.8	2.5	1.98	3.17	EP+AC	EP+AC†
5	Male	67	T11-L1	L2-L4	2:3	2:2	0.261	0.267	3	4.9	2.15	1.42	EP+AC	EP+AC
6	Female	81	L1-L3	T10-T12*	2:2	3:3	0.122	0.097	1.3	1.6	0.78	2.08	EP+AC	EP+AC
7	Male	83	T11-L1	L2-L4	3:3	3:3	0.205	0.175	2.2	2.9	1.67	1.39	EP	EP+AC
8	Male	92	T11-L1	T8-T10	4:4	4:3	0.090	0.089	1.9	1.5	1.42	1.24	AC	AC
9	Female	85	L2-L4	T11-L1	3:3	2:2	0.199	0.200	3.1	1.4	1.90	1.12	EP	EP+AC
10	Male	78	T11-L1	L2-L4	3:2	3:3	0.153	0.178	3.6	3.5	1.85	1.39	AC	AC
11	Male	76	T10-T12	L2-L4	3:4	3:3	0.138	0.237	2.0	2.4	1.45	0.89	AC	AC
12	Female	68	L2-L4	T11-L1	2:2	2:2	0.162	0.136	3.2	3.8	1.25	2.14	AC	EP+AC
13	Male	83	T10-	L1-L3	2:2	3:3	0.135	0.269	3.3	3.9	2.19	1.94	EP	EP

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			T12											
14	Male	82	L1-L3	T10-T12	3:2	2:2	0.122	0.108	2.3	1.9	0.99	1.75	EP	AC
Mean (SD)		80 (8)					0.165 (0.071)	0.172 (0.069)	2.6 (0.9)	2.8 (1.4)	1.54 (0.46)	1.60 (0.73)		

Note: The cement used for vertebroplasty is denoted as follows: C, Cortoss; P, PMMA. # Grade of disc degeneration is shown for the upper (U) and lower (L) discs of each three-vertebra specimen. + Volumetric BMD values are those of the fractured vertebra. * Cement leakage observed during vertebroplasty (leakage volume 1 ml). Fracture types defined as endplate (EP), anterior cortex (AC) or endplate plus anterior cortex (EP+AC). †In this specimen, two vertebrae sustained fracture of the endplate and anterior cortex.

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Table 2. Average (SD) results in flexed and erect posture for 36 'affected' and 16 'adjacent' discs. P values indicate main effects across the four stages of the experiment (ANOVA). Post-hoc paired comparisons indicate differences from pre-fracture ([a] $p < 0.05$; [b] $p < 0.01$; [c] $p < 0.001$) and post-fracture ([A] $p < 0.05$; [B] $p < 0.01$; [C] $p < 0.001$) values. Post-consolidation measurements were obtained following a 1 hr period of compressive loading at 1 kN following vertebroplasty to allow cement consolidation. Intradiscal pressure in the nucleus (IDP) and the size of stress peaks in the anterior (SP_A) and posterior (SP_P) annulus are given in megapascals (MPa).

		Pre-fracture	Post-fracture	Post-vertebroplasty	Post-consolidation	P
IDP- flexed (MPa)	Affected	0.80 (0.47)	0.55 (0.30)[c]	0.70 (0.34)[C]	0.66 (0.31)[bC]	<0.001
	Adjacent	0.90 (0.45)	0.78 (0.44)[a]	0.79 (0.50)	0.76 (0.45)[a]	0.016
IDP- erect (MPa)	Affected	0.75 (0.40)	0.35 (0.28)[c]	0.57 (0.29)[cC]	0.53 (0.28)[cC]	<0.001
	Adjacent	0.94 (0.39)	0.70 (0.51)[b]	0.76 (0.53)[aA]	0.72 (0.47)[b]	0.003
SP_A – flexed (MPa)	Affected	1.39 (1.17)	1.10 (0.66)[a]	1.17 (0.94)	1.26 (0.97)[A]	0.166
	Adjacent	1.58 (1.87)	0.81 (1.35)	0.90 (1.09)	1.20 (1.51)	0.120
SP_A – erect (MPa)	Affected	0.60 (0.58)	0.70 (0.49)	0.75 (0.56)	0.63 (0.48)	0.158
	Adjacent	0.62 (0.77)	0.44 (0.72)	0.52 (0.58)	0.44 (0.54)	0.457
SP_P - flexed (MPa)	Affected	0.45 (0.67)	0.86 (0.82)[b]	0.42 (0.49)[C]	0.41 (0.49)[C]	0.001
	Adjacent	0.22 (0.38)	0.76 (0.88)	0.39 (0.55)[a]	0.40 (0.54)[a]	0.109
SP_P - erect (MPa)	Affected	0.69 (0.73)	1.52 (1.09)[c]	0.92 (0.70)[C]	0.95 (0.77)[C]	<0.001
	Adjacent	0.85 (1.01)	1.17 (0.87)	0.92 (0.74)	0.84 (0.64)	0.431
F_A - flexed (%)	Affected	55.2 (17.4)	40.7 (11.7)[c]	46.9 (14.4)[aB]	46.3 (13.0)[bB]	<0.001

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	Adjacent	55.5 (21.5)	35.6 (15.1)[a]	42.4 (14.0)[a]	45.5 (19.0)	0.003
F_A - erect (%)	Affected	35.3 (13.1)	26.3 (13.2)[c]	30.4 (11.8)[aA]	29.1 (11.9)[cA]	<0.001
	Adjacent	37.1 (16.3)	27.9 (15.3)[b]	31.4 (12.5)[a]	30.2 (12.6)[a]	0.007
F_P - flexed (%)	Affected	31.4 (14.0)	32.4 (14.3)	29.3 (12.7)	26.6 (11.5)[bB]	0.005
	Adjacent	28.1 (13.5)	34.1 (15.4)	28.3 (16.2)	27.7 (15.4)	0.148
F_P - erect (%)	Affected	37.2 (14.8)	35.2 (16.9)	34.7 (15.2)	35.2 (16.7)	0.618
	Adjacent	39.5 (11.8)	38.7 (19.3)	35.6 (17).4	34.4 (15.1)	0.162
F_N - flexed (%)	Affected	13.4 (14.3)	26.9 (16.1)[c]	23.8 (15.8)[a]	27.1 (13.8)[c]	<0.001
	Adjacent	16.4 (16.9)	30.3 (15.9)[a]	29.3 (17.8)[a]	26.9 (18.8)[a]	0.022
F_N - erect (%)	Affected	28.6 (16.9)	38.2 (21.2)[b]	34.8 (17.9)[a]	36.1 (21.2)[a]	0.011
	Adjacent	21.4 (18.4)	34.3 (24.2)[b]	33.7 (22.7)[a]	34.7 (21.1)[b]	0.001

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