Introduction: Vertebroplasty is an effective and widely used procedure to stabilize osteoporotic and metastatic vertebral bodies, but concerns are raised about failure of adjacent vertebrae due to the stiffness increase associated with cement augmentation (1). Finite element (FE) analysis is a powerful tool to examine the biomechanics of vertebroplasty but so far no study used real cement distributions obtained clinically or included damage accumulation in bone. Accordingly, the goal of this study was to use a recently validated anatomy-based nonlinear FE method (2) to quantify stiffness, strength and stress distributions of vertebral bodies after vertebroplasty with different cement volumes, distributions and elastic properties.

Materials and Methods: Twelve cadaveric osteoporotic human vertebral bodies (L1-5, age 47-83) were embedded with 4-mm thick polymethylmethacrylate (PMMA) discs above their endplates, scanned with high-resolution pQCT (82μm, XtremeCT, ScancoMedical, Switzerland) and tested in compression until failure. They were augmented under fluoroscopy with various volumes of a radio opaque cement (Vertecem, Synthes, Switzerland) and scanned again. Image sets coarsened to 1312μm were segmented to define contours of vertebral bodies and injected cement and converted to FE models (Fig.1) using a method validated in uniaxial compression for the same non-augmented specimens (2). Bone was considered transverse isotropic with symmetry along the vertebra inferior-superior axis and properties defined with a novel constitutive law describing elasticity, plasticity and damage (3). PMMA discs added on both endplates had an isotropic linear elastic behaviour (3GPa modulus and 0.3 Poisson’s ratio). The region of cement injection damage (3). PMMA discs added on both endplates had an isotropic linear elastic behaviour (3GPa modulus and 0.3 Poisson’s ratio). The region of cement injection damage (3).

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Stiffness and force at 1.2mm of the augmented vertebrae increased with increasing cement modulus especially in the S+I case. The enhanced increase in stiffness and force at 1.2mm for the S+I model compared to the S/I pattern, and the effect of cement volume are qualitatively consistent with the subsequent in vitro failure tests of our samples after augmentation. The significantly greater increase in force than stiffness was also consistent with previous findings (4) although both were underestimated. The stiffening and strengthening mechanism was driven by cement pattern: cement bridging both endplates greatly reduces stresses in the cortex as it acts as a pillar to transmit stresses between the endplates. Induced stress changes may lead to middle-term bone resorption and failure in adjacent vertebrae through endplate bulging above and below the cement (1). Our results suggest that more compliant cements distributed to touch both endplates might reduce such risks by limiting stiffening while providing sufficient load resistance. This study is the first to use anatomy-based nonlinear FE models with real cement distributions and bone damage accumulation. Inclusion of a more detailed cortical shell, heterogeneous bone anisotropy and damage in the cement-bone mixture will help refine future analyses. Finally, this method can be adapted to clinically more relevant boundary conditions and will help improve the vertebroplasty technique and the related biomaterials.


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Results: Stiffness and force at 1.2mm of the augmented vertebrae increased with injected cement volume along two patterns (Fig.2a): for small volumes cement touched only one endplate (S/I) while for larger volumes it bridged both endplates (S+I). Slight increase in stiffness occurred for S/I cases, but minimal increase in force at 1.2mm was found because damage localized under and/or above the cement. Moderate stress redistribution was observed above and below the cement. S+I models behaved almost linearly with significant stiffness increase and no visible failure leading to an even more significant increase in force at 1.2mm. Stresses were reduced in the peripheral bone and strongly increased above the cement (Fig.2b). Increasing cement modulus had a slight effect on stiffness (1-2 times stiffer) and almost none on force at 1.2mm displacement for the S/I cases, but had a strong effect on S+I models which became 1-8 times stiffer and resisted 1-11 times more force than non-augmented models (Fig.3). Finally, stresses above and below the cement increased with increasing cement modulus especially in the S+I case.

Discussion: The enhanced increase in stiffness and force at 1.2mm for the S+I compared to the S/I pattern, and the effect of cement volume are qualitatively consistent with the subsequent in vitro failure tests of our samples after augmentation. The significantly greater increase in force than stiffness was also consistent with previous findings (4) although both were underestimated. The stiffening and strengthening mechanism was driven by cement pattern: cement bridging both endplates greatly reduces stresses in the cortex as it acts as a pillar to transmit stresses between the endplates. Induced stress changes may lead to middle-term bone resorption and failure in adjacent vertebrae through endplate bulging above and below the cement (1). Our results suggest that more compliant cements distributed to touch both endplates might reduce such risks by limiting stiffening while providing sufficient load resistance. This study is the first to use anatomy-based nonlinear FE models with real cement distributions and bone damage accumulation.