VOXEL-BASED FINITE ELEMENT MODELS PREDICT VERTERBRAL FRACTURE STRENGTH BETTER THAN QUANTITATIVE COMPUTED TOMOGRAPHY

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Introduction

While decreased bone mineral density (BMD) of the hip and spine correlate with increased fracture risk, dual-energy x-ray absorptiometry (DXA) and quantitative computed tomography (QCT) BMD of the spine remain only moderately correlated with in vitro vertebral fracture strength [1]. Better estimates of vertebral fracture strength are therefore expected to improve clinical fracture risk prediction for osteoporosis and may provide more sensitive methods of measuring drug treatment effects.

Finite element modeling is in theory advantageous over QCT for assessing vertebral fracture strength since it mathematically represents established mechanical principles that integrate complex geometrical and material property data. While improved predictions of fracture strength have been generated with finite element models when compared to DXA and QCT for the hip [2] and QCT for the spine [3], the general applicability of the latter is limited by its use of only six subjects and a mixture of fresh and embalmed tissue. The issue is further complicated due to the thin nature of the vertebral cortical shell and its difficulty to measure using QCT and its unknown tissue material properties.

The overall goal of this study was to establish that finite element modeling can predict vertebral body strength better than QCT. We did this by developing a theory to predict vertebral strength using both QCT and linear FEM, and by comparing these strengths against in vitro experimental measurements of vertebral fracture strength.

Methods

QCT scans were taken of 13 vertebral bodies from 13 cadavers (L1-L4; age: 37-87; M=6, F=7) using a clinical scanner (GE 9800; General Electric, Milwaukee, WI: 140kV, 70mA, 0.25 mm/pixel, 1.5 mm slice thickness, bone algorithm). Midvertebral trabecular BMD (mg/cm³) was calculated for each vertebra by using commercially-available software (QCT PRO, Mindways Software, Inc., San Francisco, CA). The vertebral bodies were then loaded to failure in compression (Figure 1a).

The QCT data were converted to bone mineral density using the calibration phantom and averaged over 1x1x1.5 mm³ volumes (Figure 1b). A finite element mesh was then generated by converting each imaging volume directly into a finite element. QCT BMD of each element (ρ, g/cm³) were converted into a longitudinal (or axial) compressive modulus (E, MPa) using the following equation [4]: E = 34.7 + 3230ρ³. The remaining transversely isotropic elastic constants were then assigned using assumptions of transverse isotropy [5]. The resultant vertebral stiffness was computed using a linear elastic analysis and boundary conditions that mimicked the experiment.

A uniform column model of the vertebra dictated that vertebral strength is equal to the product of FEM vertebral stiffness, vertebral height, and the yield strain of vertebral trabecular bone in compression (0.77% [6]; and that it is linearly correlated with the product of QCT BMD and vertebral cross sectional area (CSA). QCT BMD and finite element model stiffness were also used as independent predictors as well as input for the above formulae, all of which were compared against the experimental strength data.

Results

The best predictor of vertebral body strength was the finite element model estimate of strength followed by finite element stiffness, QCT estimate of strength (BMD*CSA) and BMD (Figure 2 and Table 1). The standard error of the regression using QCT strength was 56% larger than FEM strength. The mean (± SD) of QCT BMD was 87±36 mg/cm³ (range: 31-164 mg/cm³) with 69% of the specimens possessing values below the clinical fracture threshold of 110 mg/cm³.

Discussion

These results establish that FEM is a much better predictor of vertebral strength in vitro than is QCT. They echo the findings of similar studies for the hip [2] and confirm more preliminary studies for the spine [3]. One key feature of this study is that the procedures used for the finite element modeling involved no calibration against the predictor dataset and in that sense the test for prediction was strict and truly prospective. The range of bone quality in the specimens and the linearity of the results also suggest that these findings should apply across the clinical population of interest for osteoporotic fracture assessment. As a better predictor of vertebral strength than QCT, finite element modeling of the vertebrae — which is simple to automate — may also serve as a surrogate for fracture strength in assessment of drug treatment effects and therefore may substantially reduce the time of the studies required to demonstrate drug benefits.

Table 1 – Linear regression values between vertebral body compressive strength (Fₑ, in N) and independent variable (X). Equation: $Fₑ=aX + b$.

Acknowledgement

NIH AR41481; NSF BES-9625030; unrestricted gifts: Kyphon and Medtronic Sofamor Danek; tissue from NDR1.

References: