Predicting Vertebral Compression Strength: Quantitative CT versus MRI-Based Bone Quality

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INTRODUCTION: Accurately predicting vertebral strength is critical for surgical decision-making in lumbar spine surgery, as impaired bone quality increases the risk of perioperative fractures, screw loosening, and cage subsidence. While volumetric bone mineral density (vBMD) from quantitative CT (qCT) and MRI-based vertebral bone quality (VBQ) have been proposed as imaging biomarkers, their relative predictive value for mechanical failure remains uncertain. Abdominal aortic calcification (AAC), a marker of systemic vascular and metabolic disease, has also been associated with impaired bone metabolism and fracture risk, but its role in predicting vertebral strength is unclear. Finite element analysis (FEA) provides patient-specific estimates of vertebral compression strength (CS) but is not routinely employed in clinical practice. We hypothesized that qCT would outperform VBQ and other imaging modifiers in predicting FEA-derived vertebral CS. To test this, we aimed to identify multimodal imaging predictors of vertebral CS in patients undergoing lumbar fusion.

METHODS: Data were retrospectively reviewed from an institutional database of patients with degenerative spinal disorders who underwent lumbar fusion surgery between 2014 and 2020 at a specialized orthopedic hospital. IRB approval was obtained. Patients with preoperative lumbar CT and MRI within 12 months were eligible; exclusions included spinal fractures, prior fusion, tumors, infections, or poor-quality imaging. A total of 76 patients met criteria and were analyzed. All CT scans were performed without a phantom, and Hounsfield unit values from vertebral regions of interest at L1-L2 were converted to volumetric bone mineral density (vBMD) using scanner-specific calibration factors derived from barometric quality assurance data. $VBQ_{L1/2}$ was calculated from T1-weighted MRI as vertebral body signal intensity normalized to cerebrospinal fluid. AAC score was evaluated from lateral lumbar radiographs using the Kauppila classification.[1] Vertebral CS at L1 was calculated by FEA, in which three-dimensional CT models were generated. A compressive displacement was applied to a cement cap placed at the cranial endplate of the vertebra in ramped displacement increments of 0.01 mm/step, and CS was defined as the point at which a rapid decline occurred in the force-displacement curve under compression. Continuous variables were summarized by means ± standard deviations and categorical variables by counts and percentages. Group differences were assessed using Chi-square or Kruskal-Wallis tests. Associations between CS and imaging parameters were evaluated with Spearman correlations and multivariable linear regression adjusted for age, sex, and BMI, with checks for multicollinearity (variance inflation factor > 2.5). Model performance was compared using adjusted R^2, AIC/BIC, and ANOVA. Statistical significance was set at $p < 0.05$.

RESULTS SECTION: Seventy-six patients were included (54% female; mean age 61.1 ± 10.6 years; mean BMI 29.6 ± 6.2 kg/m²). vBMD demonstrated a strong correlation with vertebral CS ($\rho = 0.75$, $p < 0.001$). VBQ ($\rho = -0.20$, $p = 0.086$) and AAC ($\rho = -0.22$, $p = 0.062$) were not significantly correlated. In multivariable regression, vBMD was the only imaging predictor that remained significant ($\beta = 64.9$, $p < 0.001$), with male sex also contributing ($\beta = 2252$, $p < 0.001$). VBQ alone was not predictive ($p = 0.606$; adjusted $R^2 = 0.09$). Adding VBQ or AAC to vBMD models did not improve explanatory power (adjusted $R^2 = 0.77$ for vBMD alone vs. 0.76-0.78 with VBQ/AAC).

DISCUSSION:
vBMD was the only imaging biomarker that reliably predicted vertebral compression strength, underscoring its value for preoperative bone quality assessment. Given that both vBMD and FEA-derived CS are CT-based, the strong association is not unexpected. In contrast, MRI-based VBQ did not predict CS, suggesting that trabecular density captured by CT is most relevant for mechanical compression strength. VBQ may still provide complementary information related to vertebral marrow composition and metabolic changes, but not the intrinsic mechanical compression strength of individual vertebrae captured by FEA. These findings support CT-based evaluation as the most reliable method for identifying patients at risk of vertebral fragility.
Limitations include the retrospective design, single-center setting, modest sample size, and a high mean BMI in this cohort, which may limit generalizability.

SIGNIFICANCE/CLINICAL RELEVANCE: qCT-derived vBMD was the only imaging biomarker that reliably predicted vertebral compression strength, highlighting trabecular density as the key determinant of mechanical load capacity. In contrast, MRI-based VBQ likely reflects marrow composition and metabolic changes but does not capture intrinsic vertebral strength, making vBMD the most robust and practical tool for preoperative risk stratification when assessing vertebral stability, implant fixation, and fracture risk.

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