Maximal Entropy as a Predictor of Trabecular Bone Strength from High-Resolution MR Images

Laurent POTHUAUD[1], David C. NEWITT[1], Pierre LEVITZ[2], Sharmila MAJUMDAR[1]
[1]University of California, San Francisco, 1 irving street, San Francisco, CA United States; [2]Centre de Recherche sur la Matiere Divisee, 1bis rue de la ferollerie, Orleans, France;

Introduction

Trabecular bone microarchitecture characterization could be an important tool for in vivo prediction of bone strength. Nevertheless, the clinical application is actually limited due in part to the lack of predictive analytical model that utilizes microarchitecture to predict the biomechanical properties of trabecular bone. We have recently developed an in vitro exponential model linking bone stress, bone volume fraction (B_V/T_V) and connectivity (χ)(1). In this previous work, bone stress was evaluated from uniaxial compression test, while B_V/T_V and χ were directly evaluated from high-resolution Magnetic Resonance (MR) imaging. The aim of the present study was to explore the potent interest of the Maximal Entropy (ME) of high-resolution MR images to predict trabecular bone stress. Hence, our previous exponential model(1,2) was extended to the use of ME as stress axis replacement, and this new predictive model can be directly applied from MR imaging.

Methods

Fourteen lumbar vertebrae (L3) were obtained from cadavers (6 women, 8 men, 22-76 years). Mid-sagittal sections (7-14 mm thick) aligned along the superior-inferior direction were obtained from each vertebra, as well as an adjacent cylindrical trabecular bone sample was taken following the medial-lateral direction.

The cylindrical samples were mechanically tested using uniaxial compression, and the stress-strain curve was measured. The maximum stress value (S) was expressed as the maximum load (first maximum of the strain-stress curve) divided by the cross-sectional area (expressed in MPa).

The mid-sagittal sections were immersed in GdDTPA doeped saline and MR images were obtained using a 3D fast gradient echo sequence with partial echo time (TE=7ms, TR=50ms, 30° flip angle, scan-time=33min). The resolution was 300µm in the axial direction and 117x117µm in the perpendicular plane, with a matrix size of 512x512x128 16-bits encoded pixels (fig. 1).

Gray levels images were segmented following a global threshold value using a dual reference limit. Then, a clustering analysis was applied in order to check a single connected cluster of solid without internal surfaces (fig. 1).

B_V/T_V was directly evaluated from pixel counting, and χ was evaluated from Euler-Poincaré characteristic.

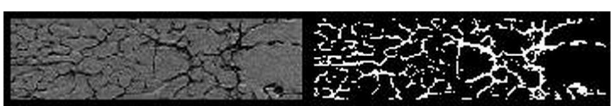

Figure 1

Entropy (E) was calculated as $E = -\sum q \, . \log[n(q)]$, where n(q) is the density of the probability function relative to the volume fraction of solid q evaluated in a cubic box of size L. Then, the maximal entropy (ME) was defined from the first maximum of the curve E(L) (fig. 2).

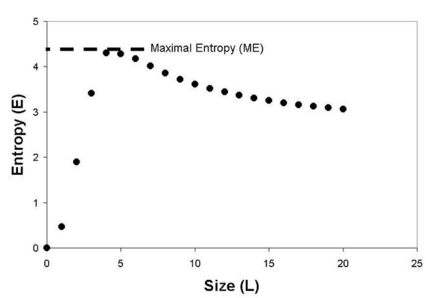

Figure 2

Results

Figure 3 shows exponential relationship between S and ME, with R^2 value of 0.88. This high statistical correlation suggest that S could be predict from ME.

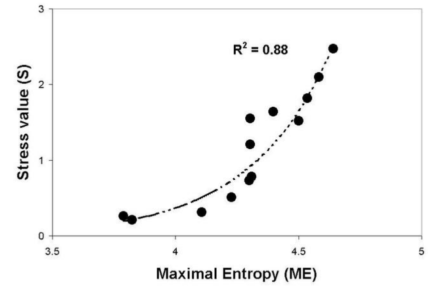

Figure 3

Using a nonlinear generalized least square fit an exponential model was obtained. This model was: $fit - ME = b_0 + b_1 \, . \exp(b_2 \, . \, B_V / T_V) \, . \, (b_3 - \chi)$, where b_0=4.87, b_1=-0.16, b_2=-8.9 and b_3=19.4. High statistical correlation (R^2=0.95) was obtained between ME and its fit-model.

The experimental points are plotted on a ($\chi'=b_3-\chi$, $ME'=b_0-ME$) axes (fig. 4), with a very good correspondence with the isocurves of constant B_V/T_V deduced from the exponential fit-model.

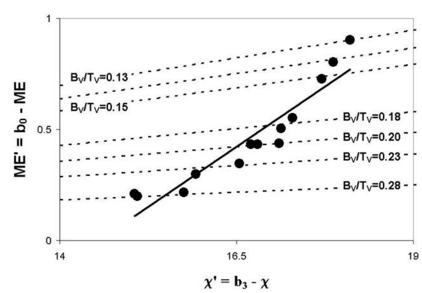

Figure 4

Discussion

In this study we have demonstrated the potential and feasibility using high resolution MR imaging of trabecular bone, and characterizing the maximal entropy of the trabecular bone, to predict bone strength. An exponential model linking entropy, connectivity and bone volume fraction was established. This model allows one to deconvolve the respective effects of B_V/T_V and χ in the prediction of ME, and indirectly of S.

Entropy of trabecular bone has been previously discussed(3), but it is the first time that Maximal Entropy is directly linked to the bone strength. The main advantage of our present model is its direct application from MR imaging, and its potential for in vivo use in the prediction of fracture risk.

Acknowledgements

We thank Dr. Olivier Beuf for the acquisition of the MR images.

References

[1]Pothuaud L., Mosekilde L., Van Rietbergen B. *et al.* Potential interest of topological parameters in the prediction of the biomechanical properties of trabecular bone. (in press)
[2]Pothuaud L., Benhamou C.L., Porion P. *et al.* (2000) Fractal dimension of trabecular bone projection is related to three-dimensional microarchitecture. J. Bone Miner. Res. 15:691-699.
[3]Gowin W., Saparin P.I., Kurths J., *et al.* (1998) Measures of complexity of cancellous bone. Technol. Health Care 6:373-390.