Estimation of cortical micromorphology from high-frequency ultrasound backscatter

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Background, Motivation and Objective

Cortical bone microarchitecture, i.e., porosity (Ct.Po), pore diameter (Ct.Po.Dm) and pore density (Ct.Po.Dn) are important factors in determining bone toughness and strength [1]. Ultrasound backscattered from cortical bone carries information about the morphology of unresolved structures, but multiple scattering, mode conversions, and attenuation caused by absorption and scattering may influence the backscatter spectrum. We have conducted a parametric sound propagation simulation study to establish the associations between pore morphology and backscatter properties and to develop a theoretical cortical bone backscatter model.

Statement of Contribution/Methods

A 2D parametric Finite-Difference Time-Domain (FDTD) study was performed using a 4-mm thick plate with randomly distributed spherical pores yielding Ct.Po (2-18%), Ct.Po.Dm (18-195 µm) and Ct.Po.Dn (< 100 mm^{-2}) . Isotropic material properties were used for bone (c_{11}=c_{22}= 23.7 GPa, c_{12}=9.5 GPa, c_{66}=6.6 GPa, ρ=1.93 g/cm³, α=2.1 dB/mm) matrix and pores (c_{11}=c_{22}= c_{12}=2.25 GPa, c_{66}=0 GPa, ρ=1.00 g/cm³, α=0.002 dB/mm). The plate was placed 4 mm below the surface of an unfocused linear array (single element size: 0.3 mm, N_{tx} = 16, N_{rx} = 32). A broadband (BW = 57 %) 6-MHz pulse was used for excitation. All simulations were performed using Simsonic (http://www.simsonic.fr/). A sliding-window spectral analysis was performed for each receive channel. Spectra originating from the plate surface were averaged and provided a reference spectrum. The apparent integrated backscatter amplitude (AIB) was derived and a plane was fitted to the normalized spectrogram $Y_{norm}(f,z)$ in frequency and depth ranges of 3.5 ≤ f ≤ 8.5 MHz and 1 ≤ z ≤ 3 mm, respectively:

$$Y_{norm}(f,z) = \alpha_0 + \alpha_z \cdot z + \alpha_{fz} \cdot f \cdot z. \quad (1)$$

Each model was generated ten times and the derived coefficients were averaged.

Results/Discussion

All pore properties were associated with at least one backscatter parameter ($0.32 \le R^2 \le 0.56$). Multivariate models could explain up to 65% of the variability of the pore properties (Table I). A unique cortical bone backscatter coefficient (BSC) model was derived (Fig. 1). Our in-silico results suggest that an universal "cortical bone backscatter coefficient" can be obtained, which would pave the path for a quantification of microstructural features not resolved by state-of-the-art x-ray imaging modalities. The effects of non-uniform gradual variations of pore size in real bones and the feasibility of this approach in vivo should be further investigated.

References

[1] Bala, Y., R. Zebaze, and E. Seeman, Role of cortical bone in bone fragility. Curr Opin Rheumatol, 2015. 27(4): p. 406-13.

Tab. 1: Multivariate prediction models.

	R^2	RMSE
$Ct.Po.Dm = f(\alpha_f)$	0.56	11.5 µm
$Ct.Po = f(\alpha_z, AIB)$	0.65	2.2 %
$Ct.Po.Dn = f(\alpha_f, AIB)$	0.50	11.4 mm^{-2}

Fig. 1: Cortical bone backscatter coefficient model *BSC(ka) = f (Ct.Po.Dm, Ct.Po, Ct.Po.Dm)*.