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Abstract

In this paper a comprehensive framework is proposed to estimate the anisotropic permeability matrix in trabecular bone specimens based on micro computed tomography (microCT) imaging combined with pore-scale fluid dynamics simulations. Two essential steps in the proposed methodology are the selection of (i) a representative volume element (RVE) for calculation of trabecular bone permeability and (ii) a converged mesh for accurate calculation of pore fluid flow properties. Accurate estimates of trabecular bone porosities are obtained using a microCT image resolution of approximately 10 μm. We show that a trabecular bone RVE in the order of $2 \times 2 \times 2$ mm^3 is most suitable. Mesh convergence studies show that accurate fluid flow properties are obtained for a mesh size above 125,000 elements. Volume averaging of the pore-scale fluid flow properties allows calculation of the apparent permeability matrix of trabecular bone specimens.

For the four specimens chosen, our numerical results show that the so obtained permeability coefficients are in excellent agreement with previously reported experimental data for both human and bovine trabecular bone samples. We also identified that bone samples taken from long bones generally exhibit a larger permeability in the longitudinal direction. The fact that all coefficients of the permeability matrix were different from zero indicates that bone samples are generally not harvested in the principal flow directions. The full permeability matrix was diagonalized by calculating the eigenvalues, while the eigenvectors showed how strongly the bone sample's orientations deviated from the principal flow directions. Porosity values of the four bone specimens range from 0.83 to 0.86, with a low standard deviation of ±0.016, principal permeability values range from 0.22 to $1.45 \cdot 10^{-8}$ m^2, with a high standard deviation of ±0.33. Also, the anisotropic ratio ranged from 0.27 to 0.83, with high standard deviation. These results indicate that while the four specimens are quite similar in terms of average porosity, large variability exists with respect to permeability and specimen anisotropy. The utilized computational approach compares well with semi-analytical models based on homogenization theory. This methodology can be applied in bone tissue engineering applications for generating accurate pore morphologies of bone replacement materials and to consistently select similar bone specimens in bone bioreactor studies.

Keywords: trabecular bone, microCT, fluid dynamics, anisotropic permeability, Darcy's law

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