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NANOINDENTATION APPLIED TO THE ESTIMATION OF ELASTIC ANISOTROPY IN HUMAN CORTICAL SECONDARY OSTEONS

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ABSTRACT

The identification of elastic properties of biological hard tissues based on the interpretation of nanoindentation results involves numerous problems: multi-scale hierarchy, heterogeneity, anisotropy, and the difficulty of fabricating representative small specimens contribute to complicate the scenario. In several studies, even if the indentation modulus ${}^{I}E$ was measured in several directions in order to characterize the anisotropy of bone, the individual indentation directions were selected on different microstructural features of the same specimen or on different specimens from the same bone. Furthermore, the experimental data were most often analyzed using the well-known method by Oliver and Pharr [1], which is based on isotropic modeling of the contact mechanics problem involved in nanoindentation: provided that the Poisson's ratio ν is assumed, the Young's modulus E for bone is obtained using ${}^{I}E = E/(1-\nu^2)$.

The purpose of this study was therefore to develop a method to estimate orthotropic elastic constants of human cortical bone secondary osteons: the method is based on the interpretation of nanoindentation data obtained from measurements in two orthogonal directions by means of the anisotropic indentation model by Swadener and Pharr [2]. This model defines ${}^{I}E$ for an elastic anisotropic half-space indented by a rigid frictionless cone as a function of the indentation direction $\mathbf{a}_3$ and the stiffness tensor $\mathbb{S}$ of the material: ${}^{I}E = {}^{I}E(\mathbb{S}, \mathbf{a}_3)$.

On 22 sites of the distal femoral shaft, nanoindentation was performed locally on the same osteon in both axial and circumferential directions (Fig. 1L). For this purpose, a new specimen mounting system was designed, which allowed indentation on two orthogonal faces and avoided specimen embedding in a polymeric medium with the related mechanical property alterations. For the experimental data analysis, a fabric-based orthotropic elastic model of lamellar bone tissue was introduced [3], which is based on collagen pattern orientations observed within osteons. To estimate the stiffness tensor $\mathbb{S}$ for the indented

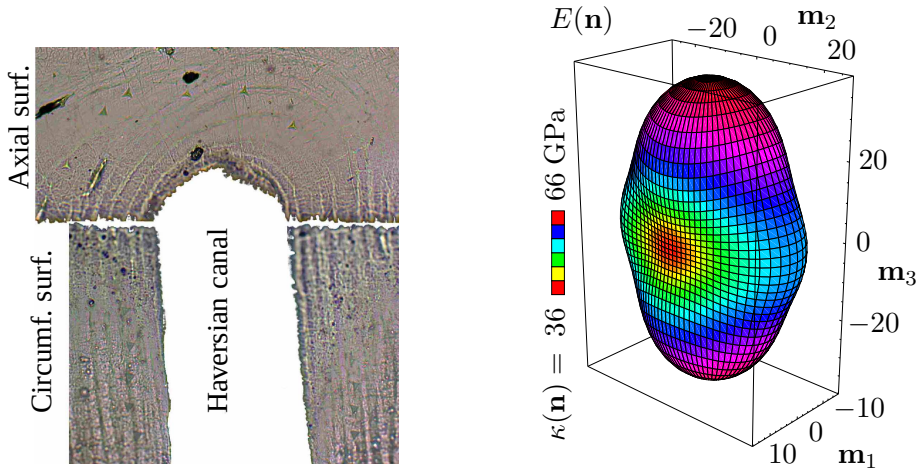

Figure 1: *(L)* An indented osteon. *(R)* Estimated elongation modulus $E(\mathbf{n})$ for the *mean* osteon with bulk modulus $\kappa(\mathbf{n})$ superimposed: $\mathbf{n}$ is a direction vector, while $\mathbf{m}_i$ are the principal material directions.

osteons, an inverse procedure based on the Swadener and Pharr model was developed and numerically implemented. A sensitivity analysis was also carried out in order to establish which parameters have a stronger influence on ${}^{I}E$: these parameters are the orthotropic Young's moduli.

Both the experimental indentation moduli and the estimated elastic constants of cortical bone secondary osteons were found to vary not only with the indentation direction, but also among different osteons of the same bone specimen. Moreover, to confirm that osteons are effectively heterogeneous in their anisotropic elastic properties, the theoretical error in the estimate of Young's moduli due by indentation misalignment was computed: if the indented surfaces are misaligned up to an angle of $10°$, the estimated Young's moduli vary only by 2%.
Finally, the elastic constants estimated for osteons showed different anisotropy ratios than those for cortical bone at the macroscopic level [4]. Using the log-Euclidean norm, the relative distance between the compliance tensors of the estimated *mean* osteon (Fig. 1R) and of cortical bone was 9.68%: osteons appeared stiffer in both their axial and circumferential material directions than cortical bone.

The proposed method for estimation of elastic constants from nanoindentation experiments can be adapted to a larger class of (bio)materials exhibiting orthotropic or higher material symmetry, for which it is possible to describe the elastic properties using a fabric-based model.

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