THE 3D ORIENTATION OF MINERALIZED COLLAGEN FIBRILS IN HUMAN LAMELLAR BONE AND ITS MECHANICAL CONSEQUENCES

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Introduction

Bone exhibits outstanding mechanical properties, achieved by assembling a mineral reinforced collagen compound in a highly organized hierarchical structure [Fratzl, 2007]. On the micron scale, the mineralized collagen fibrils (MCFs) have been assumed to have a plywood-like arrangement in osteonal bone, but the exact arrangement has so far mainly been inferred from 2D data and several, partially controversial interpretations coexist [Giraud-Guille, 1988; Weiner, 1997, Fratzl 2007]. Towards unravelling structure-function relationships at this scale, this study aimed at resolving the 3D arrangement of MCFs in human osteonal bone.

Methods

Synchrotron X-ray phase nano-tomography (SR-PNT), combining high isotropic spatial resolution (60 nm voxel size) with large field of view (90 µm) and exceptional sensitivity to local mass density [Langer, 2012], was used to study the organization of MCFs in human femoral cortical bone directly in 3D under close to native conditions. MCF orientation was measured quantitatively with the autocorrelation method within several osteonal and interstitial regions of interest in three specimens. Further, the relation between these orientations and the osteocyte (OC) lacunae locations was investigated.

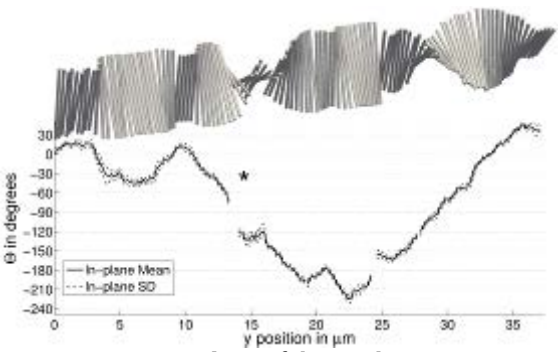

Figure 1: Mean and SD of the in-plane orientations of MCFs (Θ) across the lamellae in an interstitial region of interest, with virtual representation of the means. '': shows the location of a micro-fracture.*

Results

Results confirmed MCFs to be unidirectional in the quasi-planes of lamellae, but showed specific, less regularly organized regions. The in-plane MCF orientation (θ) across the lamellae changed smoothly (Fig. 1) and exhibited two main, consecutively coexisting motifs: oscillating plywood (OsP) and twisted plywood (TP). Mean of θ was close to the osteon axis. OsP oscillated closely around the osteon axis (offset: 6.6 ± 6.9°) with amplitude and half period being 24.2 ± 6.5° and 5.7 ± 1.2 µm, respectively. TP showed both clockwise and counter-clockwise twist directions, but at a relative constant rate (24.6 ± 2.6 °/µm). The outermost lamellae of osteons had TP arrangement, with a transition to OsP towards the Haversian canal. Mineralization was found not to be related to MCF orientation. OCs were observed to be located in OsP regions and/or adjacent to less organized zones.

Discussion

These findings are expected to promote deeper understanding of construction principles and structure-function relationships in lamellar bone tissue. In particular, the outermost TP lamella of osteons is hypothesized to have special importance in crack stopping. The quantified MCF orientations provide accurate and direct input for homogenization methods to compute mechanical properties at the coarser length scale. The lack of relation between these orientations and the local mineralization suggests that mechanical property variation of consecutive lamellae [Hofmann, 2006; Fratzl,2007; Reisinger, 2011] may predominantly be due to MCF orientation.

References

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