Variability of the Composition and Mechanical Properties of Bovine Dentin

Alix C. Deymier-Black[1], Jonathan D. Almer[2], David C. Dunand[1]

1. Department of Materials Science and Engineering, Northwestern University, Evasnton, IL USA.

2. Advanced Photon Source, Argonne National Laboratory, Argonne, IL USA.

Statement of Purpose: Biological materials such as dentin, which are composites composed of a ceramic phase of hydroxyapatite (HAP), a proteinaceous phase of collagen, and fluid filled porosity, are heterogeneous in their structure and properties [1]. Therefore, scientific testing on or involving dentin specimens can be challenging and requires the use of many samples. To facilitate orthopedic testing with dentin, it is important to identify repeatable trends in these variations allowing for better selection of a sampling population. Here, we have used high-energy x-ray diffraction, ultrasonic sound speed measurements, and thermogravimetric analysis to determine how the HAP/collagen load transfer, stiffness, and composition of bovine dentin varies between different animals, locations in the jaw, and locations within a tooth.

Methods: Eighteen bovine incisors were extracted from the jaws of five 18-month old cows. From these, 32 root dentin samples were cut from the upper (close to the crown) and lower (close to the apical tip) regions of the root so that they formed pseudo-cylinders 7.5 mm tall and with the natural cross-section of the tooth. The 32 samples were first tested at the Advanced Photon Source at Argonne National Laboratory where they were loaded in compression up to 80 MPa in increments of 20 MPa. At each load interval, high-energy wide-angle (WAXS) and small-angle (SAXS) x-ray diffraction measurements were taken at 8 different locations across each tooth in the buccal-lingual direction. From the WAXS and SAXS patterns, the lattice spacing of the HAP (00.2) planes and the spacing between HAP crystals in the mineralized collagen fibrils were determined, respectively. By comparing these spacings to the stress-free spacing, phase strains were determined for the HAP and fibrils. Apparent moduli, see Fig. 1, were calculated at each measured location. The average Young's modulus was also calculated for each dentin sample using ultrasonic sound speed measurements at a frequency of 5MHz. Finally the samples were cut into smaller sections weighing ~10mg and thermogravimetrically analyzed. They were heated from 20 to 650°C at a rate of 10°C/min and maintained at the maximum temperature for 5 min.

Results: The average HAP and fibrillar apparent moduli in the dentin samples are 26.5±7.2 GPa and 16.1±4.9 GPa respectively. The average Young's modulus as determined by ultrasonic measurements is 18.0±1.2 GPa. The average root dentin volume fractions are 40.3±1.4% HAP, 31.5±1.0% collagen, and 28.2±2.2% water. One-way ANOVA testing was used to compare the values of HAP and fibrillar apparent moduli among the sub-populations of the dentin samples. It was found that the apparent moduli were not significantly different ($p<0.1$) between different cows or different incisors. However, there was a statistical different in both the HAP and fibrillar moduli between samples taken from the lower and upper sections of root dentin. The lower sections were consistently less stiff than the upper sections. There were also significant differences in the HAP and fibrillar apparent moduli in measurements taken close to the buccal edge as compared to measurements taken close to the lingual edge of the dentin samples. The apparent moduli at the buccal edge are consistently lower than at the lingual edge.

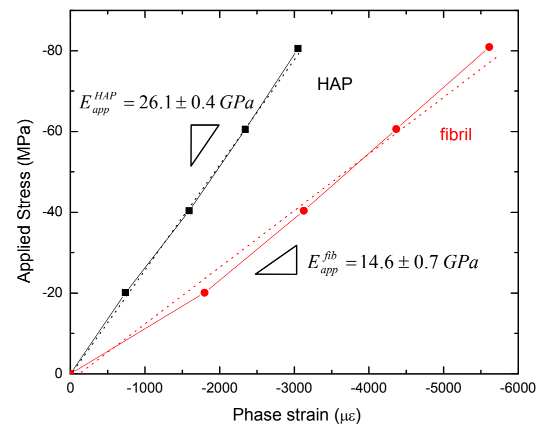

Figure 1. Representative plot of HAP and fibrillar phase strain vs. applied load. Slope of the best fit lines are the apparent moduli.

Conclusions: The value obtained for the HAP apparent modulus is in agreement with previous research done of bovine dentin [2]. The fibrillar modulus is consistently 15% lower than the ultrasonic Young's modulus. The dentin Young's modulus is likely higher due to the presence of highly mineralized peritubular dentin that does not diffract because of its lack of ordering, but acts as a reinforcement. The volume fraction of HAP in the dentin samples was lower than reported in the literature [3]. This may be due to the deciduous nature of the samples that is associated with lower hardness which is often related to a decrease in HAP content [1]. The low apparent modulus of the lower root samples may be caused by deciduous tooth resorption or the loading environment which requires the tooth to undergo stresses while embedded in the alveolar bone without damage. Similarly, the variation in apparent stiffness across the tooth may be a reinforcement strategy to minimize bending. The lack of significant differences in the apparent moduli of HAP and the fibrils between different jaws and teeth suggest that, when selecting a sampling population, there is no need to limit the samples to a single type of tooth or a single animal. However, it is important to choose samples from the same location within teeth as the elastic and load transfer properties vary in both the buccal-lingual and apical-crown directions.

References:

[1].Avery, J.K. 1994, New York, NY: Theime Medical Publishers.[2].Deymier-Black, A.C., et al. Advanced Biomaterials. 2010; Under Review.[3].Sakae, T., et al. Journal of Dental Research. 1988; 67: 1229.