Effect of Ionizing Radiation on the Modulus and Residual Strains in Bone

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Statement of Purpose: Biological tissues like bone are subject to a wide range of radiation doses during medical treatments such as cancer therapy (~ 60kGy) and terminal sterilization (~ 30kGy) (Currey JD. J Orthop Res. 1997;15:111-117). During these treatments, not only are the surrounding healthy tissues affected, but also their mechanical properties are found to degrade. Also, of great relevance is the increasing use of synchrotron x-rays in scientific studies to determine the structure and mechanical properties of these tissues, where radiation doses of 0.2 kGy/s are imparted to the sample, depending on the X-ray beam flux density. The mineral phase is less susceptible to such radiation damage; however the properties of the collagen phase have been found to change due to mechanisms such as increased cross-linking or chain scission (Barth HD. Bone. 2010;46:1475-1485). The collagen-mineral interface has also been shown to degrade due to de-carboxylation of the collagen side-chains from the surface of the mineral phase (Hubner W. Int J Artif Organs. 2005;28:66-73). Since these tissues are often located in areas which are load bearing, it is important to understand how the mechanical properties of these tissues are affected by such treatments. To investigate this effect on the elastic properties of bone, samples are subjected to a combination of mechanical loading and varying levels of radiation doses (5-3800 kGy). High-energy X-rays are employed to study the evolution of the apparent modulus and residual strain in the collagen fibrils and the mineral phase.

Methods: Bone samples were obtained from the bovine femur of an 18-month old cow, and cut into cubes of 5x4x3 mm^3 using a low-speed diamond saw under constant irrigation. The samples were tested under compressive loads at the Advanced Photon Source, Argonne National Laboratory. Four samples were subject to 7 cycles of loading interspersed with irradiation up to a pre-determined dose (maximum cumulative dose is 3800 kGy). Two samples were subject to 12 cycles of loading only. Three samples were subject to radiation only in increasing levels up to a maximum of 1500 kGy. During all loading, the samples were loaded in steps from 0 to -60 MPa. During all irradiation, a large area of the sample was exposed to the X-ray beam. X-ray diffraction measurements were taken at every load. The diffraction images were analyzed using computer routines to determine strains in the mineral phase and the collagen fibrils. The apparent modulus is given by the slope of the applied stress versus strain graph and the residual strain is the strain measurement at zero stress.

Results: The apparent moduli of the mineral (26±1.2 GPa) and fibrils (13±1.9 GPa) do not exhibit a systematic change with increasing radiation doses, as shown in Figure 1. This indicates that the rate at which load is transferred to the mineral phase via the collagen phase remains unchanged at the radiation levels applied here. However, the residual strains in the mineral phase are found to become less compressive and those in the fibrils become more compressive with increasing radiation dose and loading cycles. The loading-only and radiation-only experiments suggest that the residual strains can decrease due to both mechanical deformation (stretching of bonds) and irradiation damage (de-carboxylation of collagen side-chains). The residual strains decrease linearly with cycles as suggested by the loading-only experiment; in the radiation-only experiment the residual strains have a plateau phase up to about 60 kGy after which the strains begin to decrease rapidly. A comparison of the magnitude of the decrease and shapes of the curves indicates that the effect due to irradiation is dominant. Also, the initial residual strains in the sample served as a driving force for relaxation of strains.

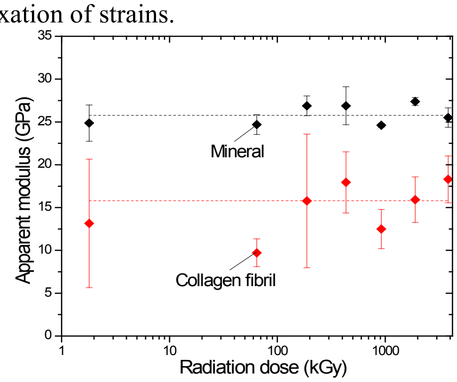

Figure 1

Conclusions: This work demonstrated that the apparent modulus of the mineral phase and the collagen fibrils did not change significantly and systematically up to doses as high as 3800 kGy. This is possible since the elastic modulus of the material is mostly dependent on the mineral phase which is more resistant to damage, and changes in the collagen phase do not significantly affect these properties. The residual strains in the mineral phase (at zero stress), on the other hand were found to become less compressive. This would indicate that de-bonding has taken place during mechanical loading, allowing the mineral platelets to relax, which re-bond on unloading the sample. Thus upon re-loading, the rate of load transfer does not significantly change from the previous cycle. It is thus important to impart as low a dose as possible to these biological tissues during experimentation and clinical therapy.