Intrafibrillar plasticity through mineral/collagen sliding is the dominant mechanism for the extremetoughness of antler bone

Abstract

The inelastic deformability of the mineralised matrix in bones is critical to their high toughness, but the nanoscale mechanisms are incompletely understood. Antler is a tough bone type, with a nanostructure composed of mineralised collagen fibrils ∼100 nm diameter. We track the fibrillar deformation of antler tissue during cyclic loading using in situ synchrotron small-angle X-ray diffraction (SAXD), finding that residual strain remains in the fibrils after the load was removed. During repeated unloading/reloading cycles, the fibril strain shows minimal hysteresis when plotted as a function of tissue strain, indicating that permanent plastic strain accumulates inside the fibril. We model the tensile response of the mineralised collagen fibril by a two – level staggered model – including both elastic – and inelastic regimes – with debonding between mineral and collagen within fibrils triggering macroscopic inelasticity. In the model, the subsequent frictional sliding at intra fibrillar mineral/collagen interfaces accounts for subsequent inelastic deformation of the tissue in tension. The model is compared to experimental measurements of fibrillar and mineral platelet strain during tensile deformation, measured by in situ synchrotron SAXD and wide-angle X-ray diffraction (WAXD) respectively, as well as macroscopic tissue stress and strain. By fitting the model predictions to experimentally observed parameters like the yield point, elastic modulus and post-yield slope, extremely good agreement is found between the model and experimental data at both the macro- and at the nanoscale. Our results provide strong evidence that intra fibrillar sliding between mineral and collagen leads to permanent plastic strain at both the fibril and the tissue level, and that the energy thus dissipated is a significant factor behind the high toughness of antler bone.

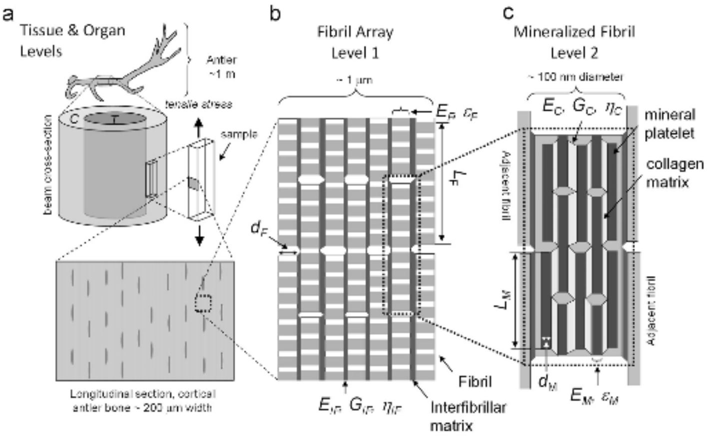

Fig. 2 – Multiscale staggered model schematic: (a) *organ and tissue level structure*: upper image shows a schematic of the whole antler, from which a cross-section (cylinder) is shown in the middle image. The outer portion of the cross section contains antler cortical bone (C) and the inner consists of tissue looking like spongy trabecular bone (T) in cross-section and is a series of empty cylinders with soft tissue in the middle. Middle right shows schematic of test specimen taken from cortical region, with tensile load applied vertically. Lower image schematically depicts the microstructure of the sample at the scale of 10–100 μm. Vertical lines schematically indicate lamellae, and ellipses indicate osteocytes. (b) *Fibril—array level structure*: at the scale of 1–5 μm, the intralamellar structure can be schematically depicted as mainly a dense array of fibrils with elastic moduli E_F. Horizontal banding on the fibrils depicts the 67-nm D-periodicity used in the SAXD measurements to measure fibril strain ε_F. Between the fibrils is a very small fraction of interfibrillar matrix (with tensile modulus E_{IF} and shear modulus G_{IF}) which is in shear strain η_{IF} (vertical dark parallelepipeds) while the fibrils are loaded mainly in tension in response to external tensile force along the vertical (Fratzl and Weinkamer, 2007; Gupta et al., 2006). As the fibrils are very long (>10 μm) the gaps at their endpoints shown in this simple schematic are highly exaggerated relative to their actual dimension; fibril length L_F and width d_F is indicated as well. (c) *Fibril level structure*: the ~100 nm diameter mineralised collagen fibril consists of mineral platelets of width d_M and length L_M (aspect ratio $\rho_2 \equiv L_M/d_M$) arranged in a staggered manner and separated by layers of collagen matrix. When the fibril is loaded in tension, the stiff mineral platelets (with tensile modulus E_M) are loaded mainly in tension (strain ε_M), with significant shear η_C in the more compliant collagen matrix (tensile modulus E_C and shear modulus G_C) between them (vertical grey parallelepipeds).