Role of inorganic components in electrical polarizability of bone tissue

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1. Research Object

Bone is a dynamic tissue that is continually formed by osteoblasts and resorbed by osteoclasts. This bone-remodeling cycle is affected by many factors including mechanical stimulation, metabolic causes, endocrine changes, and effects of medical drugs. In 1892, Wolff proposed that the functional adaptation of bone reorients the trabeculae so as to orient with new principal stress trajectories when environmental loads on bone change because of trauma or life-pattern change; this theory is known as Wolff's law. In the last 50 years, experimental and computational techniques have improved to the extent that current methods and instruments now enable quantitative study of Wolff's law. For example, Fukada et al. established the existence of piezoelectricity in heated bone specimens [1]. Bassett et al. reported that mechanical stress in mineralized tissues induces an electrical potential generated by collagen piezoelectricity [2, 3]; areas of bone under compression develop negative potentials, whereas those under tension develop positive potentials2. Indeed, negative and positive potentials may affect bone remodeling [4-8]. Living bone becomes thicker on its compressed concave side and thinner on its tensed convex side [6, 7]. In addition, bone healing is reportedly enhanced near the negative surfaces of implanted hydroxyapatite (HA) ceramics that are electrically polarized by applying an external voltage [9, 10].

Generation of electrical potential in bone by collagen displacement ceases after the collagen returns to its original location. For bone formation, however, early disappearance is inefficient and ineffective, as several weeks are required to achieve adequate bone formation during bone remodeling or fracture healing. Starting with the premise that bone remodeling requires 120–150 days, we investigated the concept of storing electrical energy generated from bone piezoelectricity. Electrical potential generated in bone by collagen displacement has been well documented [11], but we were intrigued by the role that mineral crystals play in bone piezoelectricity, which is still poorly understood. We considered the composite structure of organic and inorganic constituents and their collaborative functions in bone remodeling and chose to focus on the individual electrical properties and functions of collagen fibrils and mineral crystals. Accordingly, we studied the electrical properties of collagen fibrils and mineral crystals of bone tissue and investigated bone piezoelectricity on the basis of polarization and depolarization mechanisms.

2. Experimental Results

We plotted thermally stimulated depolarization current (TSDC) density as a function of temperature for untreated and treated cortical bone specimens. Figure 1 shows TSDC profiles for untreated specimens. For the majority of the specimens, the profile increases at 450°C, reaches a maximum at 550°C, and decreases before 600°C. Stored charge Q calculated from the curves is 7.5 μC・cm^{-2} for cortical bone cut in the transverse direction (T) and 6.1 μC·cm^{-2} for cortical bone cut in the longitudinal direction (L).

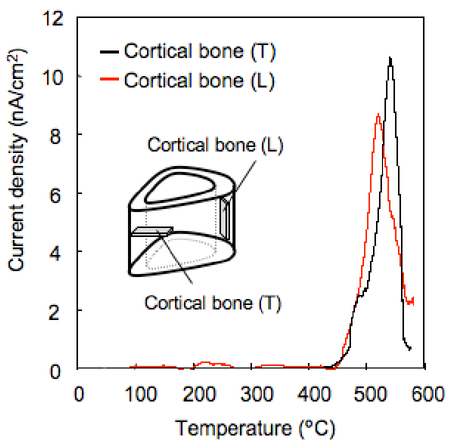

Figure1 TSDC profiles for natural cortical bone cut in the transverse (T) and longitudinal (L) directions.

Figure 2 shows TSDC profiles for specimens treated by polarization at room temperature (RT) in direct-current (dc) fields at two different external voltages. The profiles have two peaks, at about 100 and 500°C. Considering the known damage caused to organic collagen fibers at 100°C as well as TSDC profiles for decalcified bone, reported by Mascarenhas, that show peaks at 100°C [12], we speculate that the peak at 100°C is attributed to collagen fibers. Bone consists mainly of an organic matrix (such as collagen) and an inorganic matrix (such as apatite minerals), so we speculate that the peak at 500°C is attributed to apatite minerals.

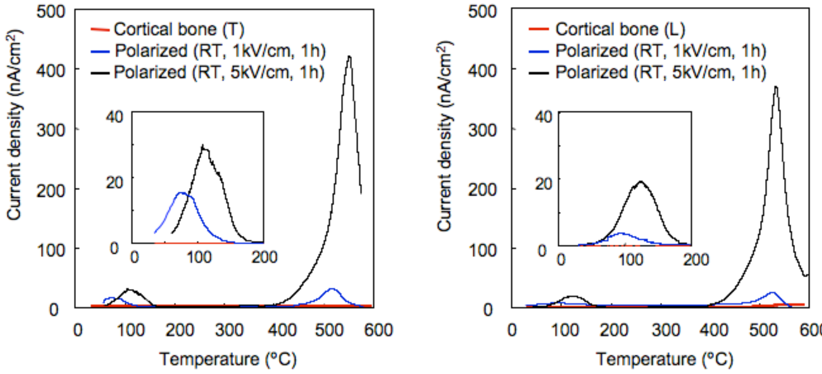

Figure2 TSDC profiles for natural cortical bone (T) and cortical bone (T) polarized at RT for 1 h at either 1 or 5 kV· cm^{-1}.

The measured energy stored by electrical polarization induced by applying an external voltage is larger for minerals than for collagen. In particular, stored energy for polarization at 1 kV· cm^{-1}, calculated from the TSDC profiles, is several times larger for minerals than for collagen, and for polarization at 5 kV· cm^{-1}, is several tenfold larger. The half periods for energy storage at 37°C, calculated from TSDC profiles, are 2–13 h for collagen fibrils and 10^7–10^{11} years for minerals. These stable charges in the minerals are enough to stimulate the osteogenic cells during bone remodeling [13].

3. References

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