International Journal of Solids and Structures 48 (2011) 603–610

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

An exponential law for stretching–relaxation properties of bone piezovoltages

Zhende Hou [a,*], Donghui Fu [a], Qing-Hua Qin [b]

[a] Department of Mechanics, School of Mechanical Engineering, Tianjin University, Tianjin 300072, China
[b] School of Engineering, Australian National University, Canberra, ACT 0200, Australia

ARTICLE INFO

Article history:
Received 23 February 2010
Received in revised form 15 October 2010
Available online 25 October 2010

Keywords:
Piezoelectricity
Bone
Piezovoltage
Relaxation
Stretched exponentials

ABSTRACT

An exponential law is presented for modeling piezoelectric behavior of bone tissues. The law is established based on experimental observation and existing empirical decay function. The model is then used to investigate the relaxation behavior of pizeovoltages induced by external load. Piezovoltages between the two opposing surfaces of bovine tibia bone samples under three point bending deformation are measured using an ultra high input impedance bioamplifier. The experimental results indicate that the pizeovoltages of bone show different relaxation behaviors during loading and unloading process. It is found that the piezovoltage decay follows a stretched exponential law when the load increases from zero to its maximum value, while it follows a typical relaxation exponential law when the load is kept its maximum value. The stretching-exponential behavior is independent of loading amplitude and rate. One possible reason for causing the stretched exponential behavior may be due to the triple helices structure of collagen fibrils distributed randomly in bone, which can experience relatively large deformation under external loads. The deformation process may include self-deformation and relative slipping between the molecule chains. The relative slipping movements may change the dielectric constants and resistances of bone, which can lead to multiple relaxation time behaviors during the deformation process of bone.

1. Introduction

Bone can change its mass, shape and density to adapt its external environment, which is called bone remodeling, the substance of Wolf law. There are generally three possible factors to influence the bone remodeling process. They are piezoelectric potential (Fukada, 1964; Bassett and Becker, 1962; Steinberg et al., 1968; Qin and Ye, 2004; Qin et al., 2005) and streaming potentials (Anderson and Eriksson, 1968; Yokota and Tanaka, 2005; Pienkowski and Pollack, 1983) both of which are known as stress generated potentials (SGPs). The third one is fluid-generated shear stress (Tzima et al., 2005; Burger et al., 2003; Riddle and Donahue, 2008). From the viewpoint of biologic evolution, though whether the electric potential of bone has any effect on remodeling is still an open question, bone's mechanical–electrical coupling property may have effects on the bone remodeling process in some way. Thus, the piezoelectricity of bone may play a certain role in bone remodeling process.

In the literature, piezoelectric signals were usually measured by charge amplifier, which detected the polarized charges on bone surfaces by transferring them to a capacitor in an instrument. This is a relatively simple way for determining the quantitative relationships between the electric charge and external force. However, this method cannot reveal the time-dependent variation of the polarized charges in bone during which the magnitude of charges may influence the bone remodeling process or osteocyte viability.

During the past decades, various new techniques have been developed and employed to investigate the piezoelectric properties of bone tissue. Based on the concept of converse piezoelectric effect (Qin, 2001), the piezoelectric coefficient d_{23} was determined using a sensitive dilatometer (Aschero et al., 1999). Piezoelectric force microscope and atomic force microscope were also employed to measure piezoelectric properties of bone (Kalinin et al., 2005; Minary-Jolandan and Yu, 2009). As bone belongs to an inhomogeneous anisotropy material, the piezoelectric coefficient matrix at a point does not convey enough information of its piezoelectric properties. In order to investigate in detail the piezoelectric properties of bone, it is necessary to conduct further studies with different methods. In this study, the piezovoltage of bone under three-point bending deformation are measured using an ultra high input impedance bioamplifier. The pizeovoltage of bone show different stretching–relaxation behaviors during loading and unloading process. It also follows different exponential law during stretching and relaxation process.

* Corresponding author. Tel.: +86 22 27406719; fax: +86 22 27892213.
E-mail address: hou@tju.edu.cn (Z. Hou).

0020-7683/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijsolstr.2010.10.024