Journal of the Mechanical Behavior of Biomedical Materials 77 (2018) 192–198

Contents lists available at ScienceDirect

Journal of the Mechanical Behavior of Biomedical Materials

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

Experimental study of time response of bending deformation of bone cantilevers in an electric field

Huimin Kang[a], Zhende Hou[a,*], Qing-Hua Qin[b]

[a] Department of Mechanics, School of Mechanical Engineering, Tianjin University, Tianjin 300072, China
[b] Research School of Engineering, Australian National University, Acton, ACT 2601, Australia

ARTICLE INFO

Keywords:
Bone
Electromechanical coupling
Electrostriction bending deflection
Polarization

ABSTRACT

Bone is a complex composite material with hierarchical structures and anisotropic mechanical properties. Bone also processes electromechanical properties, such as piezoelectricity and streaming potentials, which termed as stress generated potentials. Furthermore, the electrostrictive effect and flexoelectric effect can also affect electromechanical properties of the bone. In the present work, time responses of bending deflections of bone cantilever in an external electric field are measured experimentally to investigate bone's electromechanical behavior. It is found that, when subjected to a square waveform electric field, a bone cantilever specimen begins to bend and its deflection increases gradually to a peak value. Then, the deflection begins to decrease gradually during the period of constant voltage. To analyze the reasons of the bending response of bone, additional experiments were performed. Experimental results obtained show the following two features. The first one is that the electric polarization, induced in bone by an electric field, is due to the Maxwell–Wagner polarization mechanism that the polarization rate is relatively slow, which leads to the electric field force acted on a bone specimen increase gradually and then its bending deflections increase gradually. The second one is that the flexoelectric polarization effect that resists the electric force to decrease and then leads to the bending deflection of a bone cantilever decrease gradually. It is concluded that the first aspect refers to the organic collagens decreasing the electric polarization rate of the bone, and the second one to the inorganic component influencing the bone's polarization intensity.

1. Introduction

Bone is a kind of hard tissue that plays a critical role in supporting the whole body and maintaining the life activity of a human being. The main functions of the bone are to bear stresses and to support the weight of human bodies. In turn, external stresses can alter the structure, shape, and density of the bone to adapt to the load, known as bone remodeling, which obeys Wolff's Law. Moreover, bone has unique electromechanical behaviors, such as piezoelectric effect (Fukada and Yasuda, 1957; Qin and Ye, 2004; Qu et al., 2006) and streaming potentials (Anderson and Eriksson, 1968, 1970; Pienkowski and Pollack, 1983), which are termed as stress generated potentials in bone (SGP).

Bone is complex not only in its hierarchical structure with anisotropic mechanical properties but also in its electromechanical properties. Various methods have been developed for comprehensive understanding of the electromechanical properties of bone (Atsushi, 2015; Hastings and Mahmud, 1988; Isaacson and Bloebaum, 2010; Qin et al., 2005; Qin and Ye, 2004; Ren et al., 2015; Rosa et al., 2015). It was found that when a bone is being loaded, its piezo-voltage decay follows a stretched exponential law (Hou et al., 2011). Using a piezoelectric force microscope, Halperin et al. studied the piezoelectric effects in both, wet and dry bone at nano-scale and obtained a piezo-response image with nanometer scale resolution (Halperin et al., 2004). Aschero et al. investigated the converse piezoelectric effect of bone through measuring its bulk change induced by an electric field (Aschero et al., 1996). Wieland et al. used X-ray micro-diffraction to study the inverse piezoelectric effect of bone and measured the shear strain induced in a femur by an electric field (Wieland et al., 2015). Itoh et al. reported that charges induced by an external electric field can affect bone growth as well as osteoblast activity (Itoh et al., 2006), which indicated that electrical signals may play an important role in bone remodeling processes.

Studying the electromechanical properties of bone not only can help us to understand the nature of bone materials, but also have clinical significance. This study indicates that a square waveform electric field can makes a bone cantilever bend and the bending response of the bone with time is associated with the collagens in bone. Additional experiments reveal several aspects of the electromechanical properties of

* Correspondence to: Department of Mechanics, School of Mechanical Engineering, Tianjin University, No. 92 Weijin Road, Nankai District, Tianjin 300072, China.
E-mail address: hou@tju.edu.cn (Z. Hou).

http://dx.doi.org/10.1016/j.jmbbm.2017.09.017
Received 25 May 2017; Received in revised form 27 July 2017; Accepted 11 September 2017
Available online 13 September 2017
1751-6161/

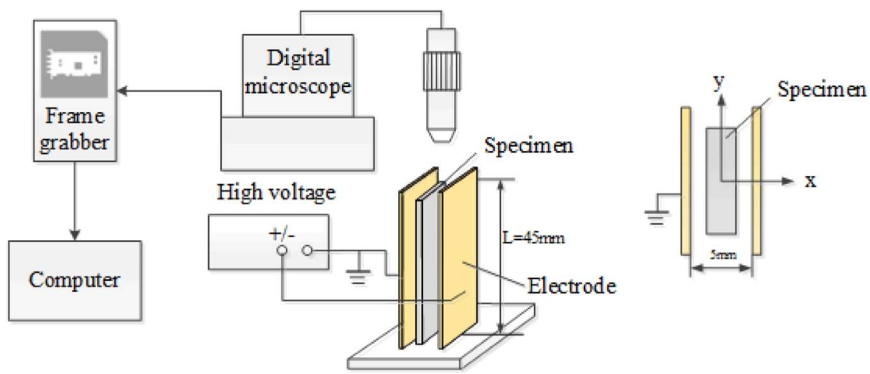

Fig. 1. Measurement system and top view of a specimen and the electrodes.

bone.

2. Materials and methods

2.1. Specimen preparation

Seven cortical bone specimens used in this study were taken from the mid diaphysis of dry degreased bovine tibias (age 2–3 years) and machined into rectangular beams with a length of 60 mm, thickness of 0.8 mm and width ranging from 7 to 8 mm. Each specimen's axes and surfaces were parallel to the axis and side surface of the diaphysis respectively.

2.2. Experimental setup

The measurement system is illustrated in Fig. 1. The specimen was clamped at its bottom end in a cantilever fashion and was placed between a pair of parallel copper plate electrodes 5 mm apart. The span of the cantilever was 45 mm. A high voltage amplifier (Trek 610D-k-CE H.V. Supply Amplifier/controller, Trek Inc.) was used to apply a voltage between the electrodes, producing a uniform electric field in the gap between them. The left electrode was grounded and the right one was connected to the voltage output terminal. The direction of the electric field could be changed by a switch on the instrument panel. A digital microscope (Hirox KH-7700, Hirox Co., Ltd.) was used to take digital images of the upper surface at the free end of the cantilever, which the total time required for capturing, converting and saving one digital image was one second. The size of the view field of the microscope was 110 μm × 82.5 μm corresponding to 1600 pixels × 1200 pixels (resolution: 0.0688 μm/pixel).

In order to investigate the time response of bending deformation of the bone specimens, the measurement system was improved by increasing its image acquisition speed. Taking advantage of the digital microscope having a VGA (Video Graphic Array) output port, a frame grabber (Mafite M1202, Liangrumei Technology Co., Ltd.) was used to convert the video signals, output from the microscope, into digital images synchronously and to save them in the computer. With this grabber the image acquisition speed reached 15 fps, as shown in Fig. 1.

2.3. Experimental procedure

A reference image was taken before an electric field was applied to the specimen. Then, a square waveform voltage with an amplitude of 3000 V was applied between the two electrodes, with the corresponding electric field intensity of 6×10^5 V/m. The waveform of the voltage was recorded by an oscilloscope (LeCroyWavesurfer 3054, Teledyne LeCroy Inc.). The duration of the waveform was about 10 s and the rising and falling edges were shorter than 0.2 ms. Once the voltage was applied, the microscope with the image grabber began to capture the deformed images at an acquisition rate of 15 fps for about 11 s. Total 150–170 deformed images were recorded for each measurement. Then, the details of the bending deflections at the free end of a specimen versus time were obtained by a correlation algorithm (Bing et al., 2009; Sutton et al., 1986) between the reference image and the deformed images.

3. Characteristics of the results

3.1. The bending feature of the specimen

In our previous work (Xu et al., 2015b), we found that a bone cantilever can be bent by the electric attractive force caused by an electric field or voltage. The deflection of the cantilever is proportional to the square of applied voltage, and its bending direction is towards the ungrounded electrode (right electrode) regardless of the sign of the applied voltages. When the right electrode is grounded, the specimen will bend towards the left. The results can be obtained from any of the seven specimens tested, and the significant results of this work are the following.

3.2. Time-response of bending of bone with and without collagens

Fig. 2 shows the measurement results of the specimen 1. The red curve is the deflection and the blue one denotes the waveform of the applied voltage. The positive deflections represent the bending direction towards the ungrounded electrode (right). The red curve shows that once the electric field is applied the bone cantilever begins to bend and its deflection increases monotonously to a peak value within about 1.6 s. After that, the deflection begins to decrease gradually during the constant voltage period, and when the electric field is removed, the deflection drops abruptly to zero.

There are two features in the deflection curve. The first one is that

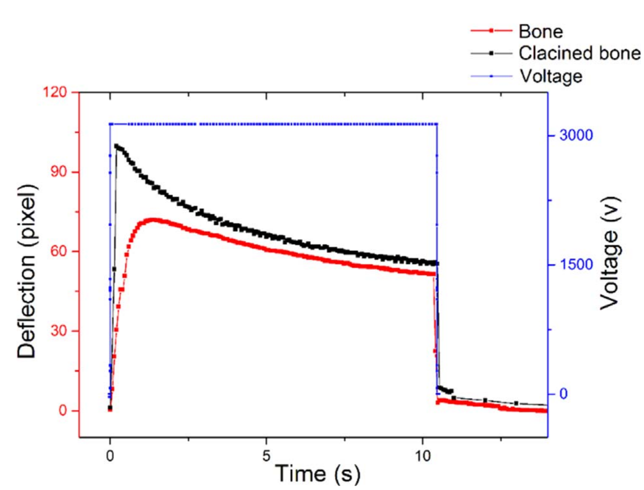

Fig. 2. Deflections versus time of specimen 1 with and without collagens. Red denotes the specimen with collagens, while the black denotes the calcined specimen. Blue denotes the waveform of the applied voltage.