Computational analysis of Strain Generated Potentials (SGPs) associated with transmission of acousto-elastic vibrations in normal and osteoporotic long bones

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1. Introduction

Electric potentials generated by mechanical strain of bones (SGPs: strain generated potentials) are one of the cofactors, which determine the adaptive remodelling processes in bone tissue [1,12,14]. The significance of the potentials SGPs in bone tissue biodynamics results from the electrosensitivity of bone cells membranes via the Ca\(^{2+}\) voltage-gated channels [7], Fig.1a. Bioelectric signals are also important in bone fractures healing: a strongly electronegative potential (the so-called fracture potential) appears immediately after a bone fracture, and during fracture healing it is normalized toward the normal bioelectric potential of a long bone [6], Fig.1b.

![Bioelectric signals](image1.png)

**Fig. 1.** a) Voltage-gated calcium(Ca\(^{2+}\)) channels in bone cells membranes and their significance in mechanical and electrical stimulation of bone tissue, [7]; b) Bioelectric fracture potential of a living long bone (tibia), [6].

It was shown by Uklejewski [12] that: 1) the piezoelectric effect in bone is associated with growth strains of bone tissue, 2) the direct generating mechanism of SGPs in bone is the electrokinetic streaming potential associated with mechanical load induced ionic fluid flow in bone pores, 3) the adequate mathematical description of the SGPs phenomenon in bone is the Biot’s theory of poroelasticity [2,3] combined with equations of linear electrokinetics. The experimental basis for this theory of the SGPs phenomenon in bone was gived by Salzstein, Pollack et al. [8] and Scott & Korostoff [9].

2. Methods

2.1. Long bone as elasto-electric transmission line

In [12,13] it was shown that it is possible for long bones: 1) to introduce the mechanical and electrical parameters per unit length of long bone shaft, 2) to treat a long bone shaft transmitting longitudinal elastic vibrations as a mechano-electric transmission line with parameters distributed practically uniformly along the line length, 3) the mechanical processes in this mechano-electric bone transmission line can be described, owing to the created electro-mechanical analogies system, as an electric equivalent in form of the system of two coupled electric transmission lines. Thus, the elasto-electric 3-path bone transmission line can be analyzed by the methods of the theory of coupled electric transmission lines.

2.2. Computational analysis of acoustoelastic SGPs in long bones shafts

We consider a long bone shaft (e.g. of the human tibia) filled with physiological fluid, and assume that at x=0 on the cross-section area of this shaft acts a longitudinal harmonic elastic load \( F(t) = F_0 \sin(\omega t) \), with a frequency \( \omega \) from 1 kHz –15 kHz. We will at first consider a normal long bone shaft, and, in the next, with: increased about 10% and 20% porosity [5]. The set of equations of elasto-electric bone transmission line was implemented in Matlab and Comsol Multiphysics computational environments. The computational simulations of electric voltages and currents values generated along the tibia shaft at various input conditions were performed.

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3. Results

In Fig. 3 there are presented exemplary results of the computational analysis: a) the distributions in direction x (i.e. along long bone shaft) of amplitudes of electric potentials SGPs and of currents for a normal long bone shaft; b) the distributions in direction x and in time t of the relative velocity $\partial(W-w)$ of ionic fluid in bone pores for a normal long bone shaft associated with the propagation of longitudinal elastic vibrations for the frequency $f=10kHz$, where $W,w$ - are the displacements of fluid and solid phases of porous cortical bone of the bone shaft.

![Fig. 3](image)

**Fig. 3** a) the instantaneous distributions in direction x of the amplitudes of electric potentials and currents in normal tibia shaft associated with the propagation of longitudinal elastic vibrations; b) the distribution in direction x and in time t of the relative velocity $\partial(W-w)$ of ionic fluid in bone pores for normal tibia shaft induced by longitudinal elastic vibrations with frequency $f=10kHz$.

From the computational analysis carried out for normal and osteoporotic long bones shaft of the tibia [4] it results that: a) the values of amplitudes of electric potentials associated with the propagation of longitudinal elastic vibrations in frequency range from 1kHz – 15kHz for a normal tibia shaft ranged from a dozen [mV] to several hundred [mV]; b) the changes of the values of density and poroelasticity of bone about 10% and 20% compared to a normal tibia shaft, produced measurable changes of amplitude values of electric potentials associated with the propagation of longitudinal elastic vibrations in tibia shaft: about 12% and 23% in comparison with values of electric potentials obtained for a normal tibia shaft; c) the distributions shapes of the analyzed quantities for osteopenic and osteoporotic tibia shafts are similar to those for normal tibia shaft.

4. Discussion

The electric signals associated with the transmission of longitudinal elastic vibrations in long shafts filled with physiological fluid can be used for monitoring the changes of poroelastic quantities of a long bone during those vibrations transmission. A method of the non-invasive determination of density and poroelasticity parameters of the long bone, elaborated by the authors, is actually patented in EPO in Munich.

References: