Bioelectrochemistry 110 (2016) 32–40

Contents lists available at ScienceDirect

Bioelectrochemistry

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

Dielectric study of interaction of water with normal and osteoarthritis femoral condyle cartilage

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ARTICLE INFO

Article history:
Received 1 May 2015
Received in revised form 26 February 2016
Accepted 13 March 2016
Available online 16 March 2016

Keywords:
Dielectric spectroscopy
Osteoarthritis cartilage
Water protons
Electrical conduction
Temperature

ABSTRACT

The main goal of this paper is the in vitro study of healthy and osteoarthritis (OA) human cartilage using the dielectric spectroscopy in the alpha-dispersion region of the electric field and in the temperatures from 25 to 140 °C. The activation energy of conductivity needed to break the bonds formed by water in the extracellular matrix takes the average values of 61 kJ/mol and 44 kJ/mol for the control and OA cartilages, respectively. At 28 °C, the small difference appears in the permittivity decrement between the control and OA cartilages, while the conductivity increment is about 2 times higher for the control tissue than that for the OA tissue. At 75 °C, the conductivity increment for both of these samples is 8 times higher than their respective permittivity decrement. In addition, at 140 °C the values of these both parameters for the OA tissue decrease by 8 times as compared to those recorded for the control sample. The relaxation frequency of about 10 kHz is similar for both of these samples. The knowledge on dielectric properties of healthy and OA cartilage may prove relevant to tissue engineering focused on the repair of cartilage lesions via the layered structure designing.

1. Introduction

The interaction of water with collagen and proteoglycan macromolecules of cartilage is one of the most important phenomena which determine physicochemical properties of this tissue such as fluid and ion flows, tensile stiffness, swelling pressures, and magnitude of electric field. The relationships between structure and electrical behavior of healthy and pathologically changed articular cartilage have previously been examined using different electrical techniques [1–7]. For example, the authors of the paper [1] applied dielectric spectroscopy to identify bioelectrical characteristics of human costal cartilage chondrocytes. This study was performed in the liquid state and at constant temperature. Other authors [2] evaluated the effectiveness of electroarthrography (EAG) to assess joint cartilage degeneration and arthritis. Moreover, Reynaud and Quinn [3] indicated that elucidation of relationships between cartilage matrix deformations and electrokinetic phenomena improves the understanding of cartilage physiology and may lead to improved tissue repair methods. Available scientific literature on the application of various electrical methods in the research of human cartilage does not provide information about the impact of wide ambient temperature range on the dielectric properties of this tissue.

The main goal of this paper is the in vitro study of healthy and osteoarthritis human cartilage using the dielectric spectroscopy in the α-dispersion region of the electric field. The results of other authors concerning this relaxation region revealed the occurrence of several types of polarization mechanisms for various biological cell [8–10] and tissues [11–14]. The simultaneous effect of the electric field and the temperature on the cartilage enables us to compare the dielectric behavior of the healthy and the osteoarthritic human cartilage at the molecular level, in order to investigate how the main components such as collagen, glycosaminoglycan (GAG) and water contribute to the measured dielectric properties of the entire tissue. Xu et al. [4], in their earlier work, revealed that changes of the cartilage matrix that occur in osteoarthritis (OA) result in a loss of the fixed ionic environment and presumably lead to a disruption of the physiological electrical fields required for normal cartilage matrix maintenance.

In our study the effect of osteoarthritis on the changes in mobility and density of the accumulated protons in the extracellular matrix of the cartilage is explained in the terms of thermal interaction of water with collagen and proteoglycan macromolecules. On the basis of the results of electrical conduction obtained in vitro in the entire cartilage tissue, it will be possible to assess the usefulness of the dielectric spectroscopy for clinical application in diagnosing its dysfunctions. However, these direct measurements of the electric properties of the knee cartilage require precise placement of the electrodes on the skin as well as the appropriate amplitude and frequency of the signal applied

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http://dx.doi.org/10.1016/j.bioelechem.2016.03.001
1567-5394/

to the electrodes to prevent any impact of the surrounding tissues, in particular the impact of the surface electromyographic (EMG) signals. The authors of the papers [5,6] have also demonstrated that in situ measurements of electric conductivity hold the promise for early detection of focal cartilage lesions. Furthermore, the knowledge on dielectric properties of healthy and OA cartilage similarly as the information about the superficial chondrocyte organization [15] may prove relevant to tissue engineering focused on the repair of cartilage lesions via the layered structure designing. Since collagen and GAG have been used as scaffolds for the tissue engineering [16], therefore, for the purpose of this paper, the application of the dielectric spectroscopy to study the relaxation phenomena associated with the decomposition of water in the collagen–GAG system of the cartilage — was fully grounded.

2. Practical models and definitions

The electrical properties of tissue as a function of the frequency of an applied voltage across the electrodes and temperature can be obtained by measuring the electrical resistance and capacitance of the whole system, which is related to the electrode and the bulk tissue. This system [17] is represented by a parallel arrangement of a resistor R_z and a capacitor C_z (Schematic 1a).

If the voltage source in this circuit is given by $u(t)=U\sqrt{2}\sin\omega t$, where U is the root-mean-square (rms) voltage and ω is the angular frequency, then the resulting current i(t) is governed by $i(t)=I\sqrt{2}\sin(\omega t-\psi)$, where phase angle ψ between voltage and current is $\psi=-\arctan R_z\omega C_z$, and the current I is given by:

$$I = YU \tag{1}$$

where the admittance magnitude Y of this circuit is:

$$Y = \sqrt{\left(\frac{1}{R_z}\right)^2 + (\omega C_z)^2}. \tag{2}$$

The impedance magnitude Z of the series representation of a parallel combination of R_z and C_z is given by:

$$Z = \sqrt{\left(\frac{R_z}{1+(R_z\omega C_z)^2}\right)^2 + \left(\frac{R_z^2\omega C_z}{1+(R_z\omega C_z)^2}\right)^2}. \tag{3}$$

The circuit model depicted in Schematic 1a can be transformed to the equivalent series circuit model [8,18–21] shown in Schematic 1b. In this circuit, the bulk tissue is represented by a parallel arrangement of a resistor R and capacitor C in series with the electrode–tissue interface modeled by a series combination of a resistor R_p and capacitor C_p. Effects of fringing field occurring between the bulk tissue and its external environment are represented by a capacitor C_f in parallel with this tissue. The above model (Schematic 1b) is then equated to an equivalent series arrangement as shown in Schematic 1c.

Since, the magnitude of the impedance Z of the circuit in Schematic 1b is considered to be equal to the impedance magnitude of the circuit in Schematic 1a, therefore Eq. (3) for the circuit in Schematic 1c becomes:

$$Z = \sqrt{(R_p + R_x)^2 + \left(-\frac{1}{\omega C_p} - \frac{1}{\omega C_x}\right)^2}, \tag{4}$$

where:

$$R_x = \frac{R}{1+[R\omega(C+C_f)]^2}, \tag{5}$$

$$C_x = (C+C_f)\frac{1+[R\omega(C+C_f)]^2}{[R\omega(C+C_f)]^2}. \tag{6}$$

By use of Eqs. (3)-(6) the magnitude of resistance R_p and capacitive reactance $1/\omega C_p$ can be obtained:

$$R_p = \frac{R_z}{1+(R_z\omega C_z)^2} - \frac{R}{1+[R\omega(C+C_f)]^2} \tag{7}$$

$$\frac{1}{\omega C_p} = \frac{R_z^2\omega C_z}{1+(R_z\omega C_z)^2} - \frac{R^2\omega(C+C_f)}{1+[R\omega(C+C_f)]^2} \tag{8}$$

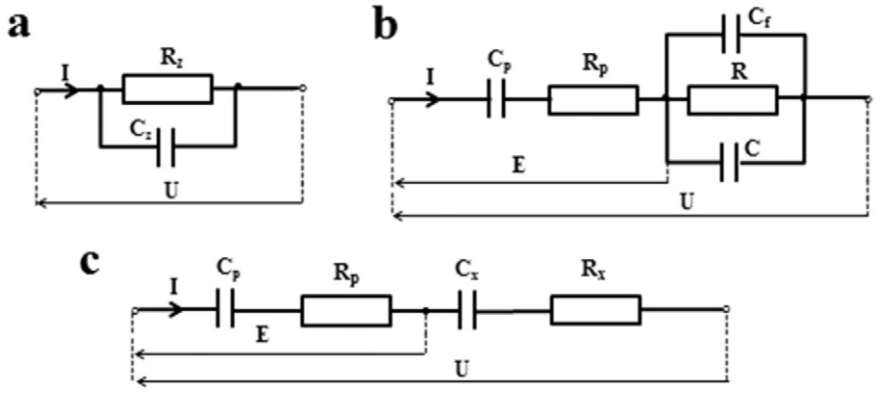
The polarization voltage E of the electrode can be obtained from the relationship:

$$E = Z_p I \tag{9}$$

where I is represented by Eq. (1) and the polarization impedance magnitude Z_p is given by:

$$Z_p = \sqrt{(R_p)^2 + \left(-\frac{1}{\omega C_p}\right)^2}. \tag{10}$$

The intrinsic electrical properties (relative permittivity ε′, dielectric loss ε″ and conductivity σ of the bulk tissue located between two electrodes of area S and separation d are defined in terms of the



Scheme 1. (a) Electric circuit for measuring the tissue–electrode system containing a parallel configuration of a resistor R_z and capacitor C_z. The input current (rms) to the circuit is I and the voltage (rms) source is U. (b) Equivalent circuit containing a series combination of the series-equivalent R_p–C_p of electrode and the parallel-equivalent R–C of bulk tissue, including a capacitor C_f modeling the stray capacitance. The polarization voltage is E. (c) Equivalent circuit containing a series combination of capacitive and resistive elements. Resistor R_x and capacitor C_x model the electrical properties of the bulk tissue including the artifact associated with the fringing fields; resistor R_p and capacitor C_p model the polarization resistance and the polarization capacitance of the electrode, respectively.