Non-Homogeneous Electromechanical Properties of Articular Cartilage Predict an Electrical Potential of Positive Polarity Outside Cartilage

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Introduction: Recently, a medical device for the quantitative assessment of articular cartilage electromechanical properties during arthroscopy was developed [1]. This device measures electrical potentials induced when the cartilage is compressed, using 37 microelectrodes evenly distributed over the surface of a hemispherical indenter. As expected, the electrical potentials measured on the indenter surface in contact with the cartilage are negative. However, an unexpected potential of positive polarity was detected on the indenter surface peripheral to the contact zone with the cartilage [2]. One hypothesis for the origin of this positive potential is the creation of a net electrical charge by the convective displacement of mobile ions within the double layer located at the cartilage-bath interface [3]. In this study, we examine a second hypothesis that non-homogeneous electromechanical properties of articular cartilage can also create positive potentials peripheral to the contact area.

Materials and Methods: In experiments using the electromechanical indentor, the articular cartilage is compressed rapidly (> 0.2mm/s) such that volumetric changes are small and diffusion potentials may be neglected [4]. In this case, the phenomenological coupling equations (Eq.1) used previously [5] will be utilized. U is the fluid flow velocity relative to fixed charge inside cartilage, J is the electrical current, p is the hydraulic pressure, Φ is the electrical potential and k_{ij} are coupling constants. Eq.2 is deduced from Eq.1 resulting in U depending on p and J. In this study, we assume that J has a small effect on U compared to p. Thus, U will follow Darcy's law and the displacement of the solid phase and p will be found from classical poroelastic equations [6] using finite element methods (FEM) with FEMLAB®. The solid phase is represented by a homogeneous and non-linear fibril-reinforced network [7]. With J given by Eq.1, the electrostatic continuity law and the assumption that the free charge density is constant with time one can demonstrate Eq.3. With a known p distribution, Φ is computed with the adequate boundaries conditions from Eq.3 by the FEM. The coupling constants k_{21} and k_{22} were computed from a published microscopic model [8] of electrolyte flow around charged GAG. The region associated with GAG is computed from a relation provided by [9] and the GAG concentration is assumed to linearly depend on cartilage depth as measured by [10]. All materials constants were representative of bovine shoulder cartilage and taken from [11].

$$\begin{pmatrix} \vec{U} \\ \vec{J} \end{pmatrix} = \begin{pmatrix} -k_{11} & k_{12} \\ k_{21} & -k_{22} \end{pmatrix} \begin{pmatrix} \vec{\nabla} p \\ \vec{\nabla} \Phi \end{pmatrix} \qquad (1)$$

$$\vec{U} = -k\vec{\nabla} p - k_e \vec{J} \cong -k\vec{\nabla} p \qquad (2)$$

$$\vec{\nabla} \cdot \vec{J} = \vec{\nabla} \cdot \left(k_{21}\vec{\nabla} p - k_{22}\vec{\nabla}\Phi \right) = 0 \qquad (3)$$

Results: For the following simulations results, a 1mm thick cartilage layer is compressed between a 3.175mm radius hemispherical indenter and a plate (both non-conductive, impermeable and rigid). The model predicts that inside cartilage the electrical potential is negative and nearly follows the form of the hydrostatic pressure distribution, while outside the cartilage a positive potential is predicted (Fig.1). A current loop was also predicted to span over the whole cartilage thickness and even extent outside the cartilage into the bath. Similar results were obtained in unconfined compression with a positive potential outside the cartilage and a current loop that were proportional to the gradient in GAG with depth [11]. The measured electrical potential profile induced when bovine articular cartilage was compressed with the device described in [1] agreed with the electrical potential calculated by the model (Fig.2).

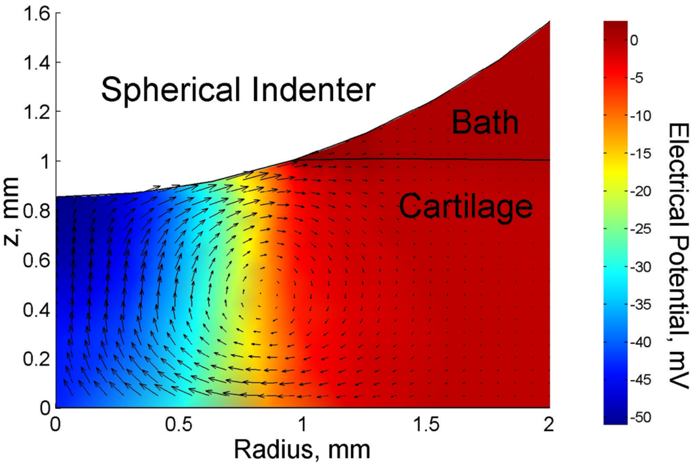

Figure 1: Cross-sectional axisymmetric view of the calculated electrical potential. Arrows correspond to electric current.

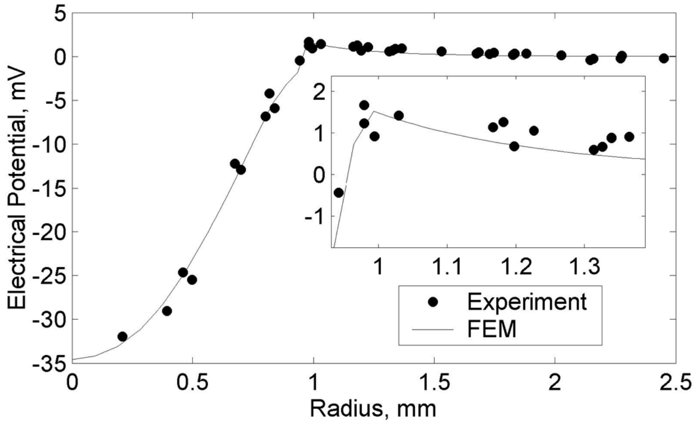

Figure 2: Comparison of the model prediction to experiment measurement of the electrical potential profile on the hemispherical surface of the indenter.

Discussion: Current loops inside loaded cartilage were previously predicted [12] however the spatial nonhomogenieity of coupling coefficients was due to cartilage volumetric changes rather than being intrinsic to the cartilage as in our study. Both types of nonhomogeniety create current loops since fluid flow is not collinear with the gradient of the coupling coefficients. This creation of positive potentials by current loops arising from nonhomgogenities described here is now a second mechanism in addition to that described previously [3]. Both mechanisms are now being tested experimentally. We hope to improve our understanding of the complex electric potential profile generated in loaded cartilage in order to maximise the diagnostic power of a streaming potential based clinical instrument for cartilage assessment.

References: [1] Garon *et al., Trans. ORS*, 32:629, 2007. [2] Quenneville *et al., Trans. ORS*, 29:528, 2004. [3] Quenneville *et al., J. Mem. Sc.*, 265:60-73, 2005. [4] Sun *et al., J. Biomech. Eng.*, 126(1):6-16, 2004. [5] Frank *et al., J. Biomech.*, 20(6):629-39, 1987. [6] Mow *et al., J. Biomech. Eng.*, 102(1):73-84, 1980. [7] Li *et al., Clin. Biomech.*, 14(9):673-82, 1999. [8] Eisenberg *et al., Physicochem. Hydrodyn.*, 10:517-39, 1988. [9] Bushmann *et al., J. Biomech. Eng.*, 117(2):179-92, 1995. [10] Legare, M.Sc.A. Ecole Polytechnique, 1998. [11] Garon, Ph.D. thesis, Ecole Polytechnique, 2007. [12] Levenston *et al., J. Appl. Mech.*, 66(2):323, 1999.

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