A NOVEL APPROACH FOR PREDICTING DIAGNOSTIC ELECTRIC POTENTIALS IN CARTILAGE

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INTRODUCTION

The ability of streaming potentials to assess cartilage function and degradation has been previously confirmed [1,2]. We are developing an electric potential-based arthroscopic device for the evaluation of articular cartilage (Arthro-BST™**), where negative electric potentials are expected under its spherical indenter containing a microelectrode array. However, this instrument also revealed positive potentials extending into the bath region that were not predicted by current electromechanical models [3]. These positive potentials require investigation since they can both affect negative potentials inside the tissue and could also contain important diagnostic information. Towards this end, we developed a model of electrolyte transport across a charged membrane that predicted the creation of net charge at membrane interfaces due to convection [4]. By further examining this model we found that net space charge was created whenever the convecting electrolyte passes through a region where fixed charge varies spatially, leading us to discover a simpler macroscopic approximation that appears capable of predicting both positive and negative potentials in loaded articular cartilage. Here we compare this approximation to previously published data for confined compression of articular cartilage [5a], as an example of this novel approach to modeling cartilage electromechanics.

METHOD

Macroscopic Approximation: Articular cartilage with a fixed charge density distribution, $\rho^0_{FCD}(\bar{z})$, is bathed in an mono-monovalent electrolyte solution at concentration c_0. At steady state, the extended Nernst-Planck flux equations for each ion can be combined to represent zero current (due to open circuit boundary conditions) to result in:

$$-D^+\bar{\nabla}c^+ + D^-\bar{\nabla}c^- - \frac{F}{RT}\left(D^+c^+ + D^-c^-\right)\bar{\nabla}\Phi + \left(c^+ - c^-\right)\bar{U} = 0 \qquad (1)$$

where counter- and co-ion concentrations c^+ and c^-, the electric potential Φ, the electrolyte velocity relative to the matrix fixed charge $\bar{U}$ are functions of the position, $\bar{r}$. D^+ and D^- are ion diffusion constants, F Faraday's constant, R the ideal gas constant and T the absolute temperature. Assuming equality of ion diffusion coefficients D, quasi-electroneutrality and neglecting diffusion fluxes, the local macroscopic electric field can be expressed as:

$$-\bar{\nabla}\Phi \cong \frac{RT}{2F^2D}\frac{\rho_{FCD}}{\sqrt{\left(\frac{\rho_{FCD}}{2F}\right)^2 + c_0^2}}\bar{U} \qquad (2)$$

Confined compression model: The linear biphasic solution [5b] for sinusoidal confined compression problem was used to calculate relative velocity and fixed charge density, the latter according to:

$$\rho_{FCD}(\bar{z}) = \frac{\rho^0_{FCD}(\bar{z})}{\left(1-\varepsilon(\bar{z})\right)} \qquad (3)$$

where $\bar{z}$ is the thickness-normalized depth in the sample, ε is the local deformation and $\rho^0_{FCD}(\bar{z})$ the equilibrium fixed charged density distribution. Cartilage thickness, L = 0.75 mm, aggregate modulus, H_A = 1 MPa, and open circuit permeability, $k = 3\times10^{-15}$ m^4/N·s, were taken as published [5a] and the effect of a deformable porous platen in series with the sample was accounted for as described previously [5b]. Since $\rho^0_{FCD}(\bar{z})$ was not reported, simulations with uniform fixed charge density of -50, -100 and -200 mEq were performed.

RESULTS

Relative velocity, fixed charge density, net space charge density and electric potential distributions are shown in Fig. 1. Electric variables were calculated using Eq. (2) in combination with Poisson's equation after setting the potential to zero far into the bath. Comparison of this model with experimental data [5a] for different ρ^0_{FCD} at c_0 = 0.001M over the frequency range from 0.005 to 1 Hz (Fig. 2 Left), and at 0.1 Hz for electrolyte concentration ranging from 0.0001 to 10 M (Fig. 2 Right) showed a remarkably high level of agreement. In Fig. 2, the elastic constant of the porous platen was taken as published (Left) or used to match potential values at 0.001 Hz for the individual sample (Right).

DISCUSSION

The relative fluid velocity is maximal close to the surface and decreases to zero on the impermeable platen ($\bar{z}=1$), while compaction of the cartilage close to the compressed surface increases the local fixed charge density (Fig. 1). These two parameters combine according to Eq. (2) to produce a net space charge distribution; forced convection through this fixed charge density distribution creates a very high positive electric charge at the compressed surface (Fig. 1) that is balanced by the negative electric charge distribution observed inside the cartilage. The capabilities of this model are reflected by its ability to predict the electric potential measured over large frequency and concentration ranges where adjustment of $\rho^0_{FCD}(\bar{z})$ had negligible consequences at low ionic strengths (Fig. 2 Left), but significantly influenced the predictions at physiological and higher ionic strengths (Fig. 2 Right).

CONCLUSION

A new macroscopic local field approximation was able to predict previously measured electrical potentials produced in confined compression. This novel approach requires only the relative velocity and fixed charge distributions and is local in nature so that it can also be applied to more complex 3D geometries, as for example, spherical indentation produced by the arthroscopic instrument (Arthro-BST™**). Since relative velocity is highly sensitive to intrinsic mechanical properties of the cartilage we may reasonably expect the combination of this new model and the electric potentials measured by the instrument to provide accurate data reflecting the function of articular cartilage at tested sites. Further examination of the ability of the model to predict experimental data is underway in addition to relating this new approach to previous phenomenological [5b] and triphasic theories [6].

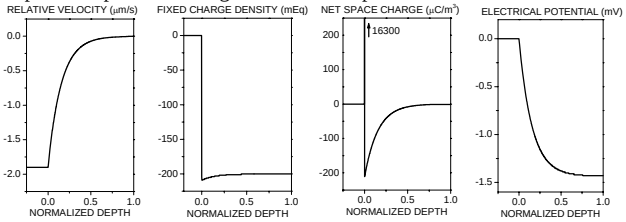


Fig 1. Relative velocity, fixed charge density, net space charge density and electric potential as a function of normalized depth ($\bar{z}$) during compression at 0.1 Hz in a 0.001 M NaCl bath ($\rho^0_{FCD}(\bar{z})$ = -100 mEq).

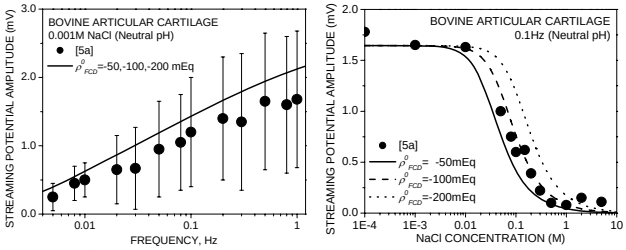


Fig 2. Left: Prediction of the electric potential (superimposed for the different ρ^0_{FCD}) with the data of [5a] at c_0 = 0.001M NaCl for frequencies 0.005 to 1 Hz. Right: Prediction of the electric potential amplitude (for the different ρ^0_{FCD}) with the data of [5a] at 0.1 Hz for concentrations ranging from 0.0001 to 10 M.

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