• POSITIVE ELECTRIC POTENTIALS DETECTED AT THE CARTILAGE/BATH INTERFACE DURING COMPRESSION AND THEIR IMPORTANCE IN CLINICAL CARTILAGE DIAGNOSTICS

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INTRODUCTION: A diagnostic instrument for the evaluation of articular cartilage during arthroscopy has been developed based on measurements of electric (streaming) potentials generated at the surface of cartilage during compression (Arthro-BST™**). A microelectrode array positioned on the indenter surface, allows the mapping of the electric potential distribution during indentation. We have measured negative electric potentials inside the cartilage during compression, as predicted by current electromechanical models [1,2]. However in recent experiments, we have also detected a positive electric potential at the cartilage/bath interface that extends rather into the bath. Current models do not predict this positive potential. The source of this positive potential requires investigation since it can both affect negative potentials inside the tissue and could also contain important diagnostic information. In this study we have characterized these positive potentials and proposed an explanation of their origin.

METHOD: Cartilage samples (2x2cm) with a layer of subchondral bone (1cm) were harvested from bovine shoulders and were tested after storage at -80°C. Indentation measurements: A linear electrode array (37 gold electrodes, dia.=75µm, spaced 185µm apart) was distributed over the surface of a cylindrical ($r_{curv.}$=2.1mm), smooth and impermeable indenter. This indenter, attached to the vertical linear motion actuator of a mechanical tester (Mach-1™**), was used to perform ramp-release indentations (300µm at 100, 200 and 1000 µm/s) in 0.01, 0.05, 0.15 or 0.5M NaCl bathing solution on several cartilage samples (n=30). Unconfined measurements: A linear electrode array (8 Pt electrodes, dia.=50µm, spaced by 300µm) was exposed over the bottom surface of an unconfined compression chamber to record electrical potentials. Cartilage disks (n=5), 1.54mm thick, 3mm diameter, without bone, were positioned such that the potentials were recorded along the disk radius with 3 electrodes under the disk and 5 in the bath. Ramp-release compressions (300µm at 25µm/s) in either 0.01 or 0.15M NaCl bathing solution were performed and the potential distributions were recorded.

RESULTS: Negative potentials inside the cartilage and positive potentials in the bath were observed in both indentation and unconfined compression geometries (Figs 1 & 2). The amplitudes of both the positive and negative potentials were reduced when salt concentration was increased (Fig 3). The potential ratios |pos./neg.| were 33.7, 21.4, 12.9 and 6.1%, respectively at 0.01, 0.05, 0.15 and 0.5M NaCl at 1000µm/s. These ratios were on average 15% lower at 100µm/s.

DISCUSSION: Electric potentials measured in the cartilage region, for indentation and unconfined compressions (Figs 1-3), behave similarly to predictions of current electromechanical models [1,2]. These negative potentials decrease with increasing salt concentration due to a reduction in Debye length and therefore a reduced extent of net space charge between adjacent glycosmainoglycans. They increase in amplitude with higher compression speed due to higher interstitial fluid pressures. However, for both indentation and unconfined compression, positive potentials were found in the bath region that are different from current model predictions. One major finding is that the potential in the bath next to the cartilage boundary is not zero, contrarily to what was generally assumed. Rather, this potential is positive, reaches its maximal value at the cartilage/bath interface and returns to the ground level quite far out into the bath (~mm). The amplitude of this positive potential is reduced with increasing salt and reduced compression speed, as with negative intratissue potentials, suggesting that similar microscopic phenomena are at play. Another interesting observation is that the |pos./neg.| potential ratio is function of salt concentration and speed. We propose an explanation for these observations based on the creation of a net positive space charge issuing from the cartilage at the cartilage/bath interface, due to fluid flow-induced displacement of the equilibrium ionic distributions (Na^+, Cl^-). At equilibrium, the electrical potential at the cartilage/bath boundary can be approximated using the linearized Poisson-Boltzmann equation:

$$\nabla^2\Psi = k^2\Psi - \frac{\rho_{cart}}{\varepsilon} \quad in\ Cartilage,\ and\ \nabla^2\Psi = k^2\Psi \quad in\ Bath \qquad (1)$$

where Ψ is the potential, $1/k$ is the Debye length, ρ_{cart} is the fixed charge density in the cartilage, and ε is the permittivity. Using Boltzmann ionic distributions, the solution to Eq. 1 takes the form of a "double-double" layer [3], extending a distance $1/k$ inside the cartilage and over $1/k$ into the bath (Fig 4). During compression, water exudes from the cartilage and slightly displaces the equilibrium ionic concentrations creating a net positive surface charge ($F*((Na^+\text{-}Cl^-)_{Fq.} - (Na^+\text{-}Cl^-)_{Fluid\ Flow})$) at the cartilage/bath interface (Fig 4). This flow-induced positive charge issuing from the interface will be greater at lower salt concentrations (increased Debye length) and will increase with higher compression speed (higher interstitial fluid velocity) and is therefore a likely source of the experimentally observed positive potentials extending quite far (~1mm) into the bath and somewhat into the cartilage.

CONCLUSION: In addition to serving as a useful diagnostic indicator of cartilage health status and function, compression-induced electric potentials and associated boundary conditions can influence cartilage mechanical behavior and the chondrocyte response to mechanical load. The positive electric potentials characterized in this study were associated with interstitial fluid flow convecting mobile ions out of the cartilage at the cartilage/bath interface. As such, these positive potentials may be exploited to preferentially reflect cartilage surface properties including intactness of the collagen network and presence of physiological concentrations of proteoglycan in superficial layers. These results also indicate the need to extend certain aspects of existing electromechanical models of articular cartilage in order to account for these new observations.

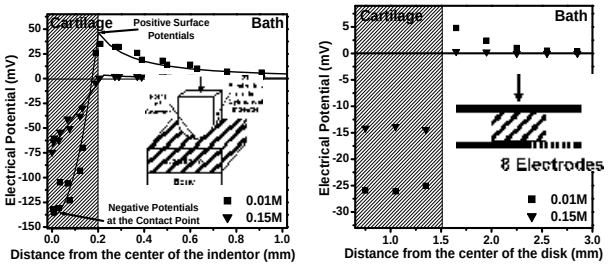


Fig 1. Potential distribution at 300µm compression (200µm/s) along the cylindrical indenter in 0.01 and 0.15M NaCl. **Fig 2.** Potential distribution along the radius of a 3mm cartilage disk at 300µm compression (25µm/s) in 0.01 and 0.15M NaCl.

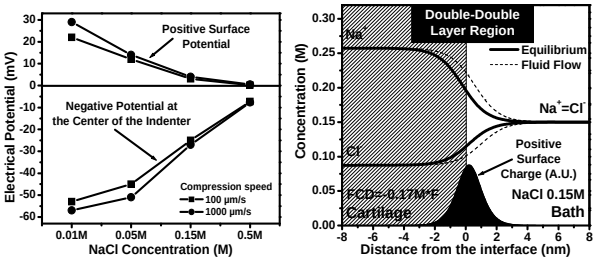


Fig 3. Influence of salt concentration and compression speed on the positive potential at the cartilage/bath interface and the negative potential at the center of the indenter. **Fig 4.** A net positive charge can be created at the cartilage/bath interface during compression due to fluid flow through the "double-double" layer, entraining different concentrations of positive and negative mobile ions.

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