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The Influence of Electric Charge Transferred During Electro-Mechanical Reshaping on Mechanical Behavior of Cartilage

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ABSTRACT

Electromechanical reshaping (EMR) of cartilage has been suggested as an alternative to the classical surgical techniques of modifying the shape of facial cartilages. The method is based on exposure of mechanically deformed cartilaginous tissue to a low level electric field. Electro-chemical reactions within the tissue lead to reduction of internal stress, and establishment of a new equilibrium shape. The same reactions offset the electric charge balance between collagen and proteoglycan matrix and interstitial fluid responsible for maintenance of cartilage mechanical properties. The objective of this study was to investigate correlation between the electric charge transferred during EMR and equilibrium elastic modulus.

We used a finite element model based on the triphasic theory of cartilage mechanical properties to study how electric charges transferred in the electro-chemical reactions in cartilage can change its mechanical responses to step displacements in unconfined compression. The concentrations of the ions, the strain field and the fluid and ion velocities within the specimen subject to an applied mechanical deformation were estimated and apparent elastic modulus (the ratio of the equilibrium axial stress to the axial strain) was calculated as a function of transferred charge. The results from numerical calculations showed that the apparent elastic modulus decreases with increase in electric charge transfer. To compare numerical model with experimental observation we measured elastic modulus of cartilage as a function of electric charge transferred in electric circuit during EMR. Good correlation between experimental and theoretical data suggests that electric charge disbalance is responsible for alteration of cartilage mechanical properties.

Keywords: cartilage reshaping, electromechanical reshaping, cartilage mechanical properties, triphasic theory

1. INTRODUCTION

Shaping cartilage in the head and neck is required to correct damage that resulted from trauma, cancer surgery or congenital malformation or recreate a missing structure. Traditional surgical reshaping techniques involve incising, suturing, curving and crushing cartilage or donor grafts [1]. Typically, restorative and cosmetic procedures involving these cartilage reshaping methods are performed under general anesthesia, require long operation time and recovery time and associated with high hospital and surgeon fees. Donor site morbidity, uncontrollable warping and shape memory effects are additional disadvantages of traditional methods [1, 2].

Recently, alternative non-surgical methods of cartilage reshaping have been introduced. Thermally mediated cartilage reshaping involves mechanical deformation of cartilaginous structure into a desired shape with simultaneous heating [3]. When cartilage temperature is raised to transition level of approximately 70 °C relaxation of internal stress occurs and new stable shape is produced. Corrections of septal deviation and reshaping of protuberant ears have been performed using fiber-delivered laser light as a heat source. Another non-surgical cartilage reshaping technique is electromechanical reshaping of cartilage (EMR) [4, 5]. It relies on application of low-level electric voltage to mechanically deformed cartilage. It has been suggested that electrochemically induced relaxation of internal stress is produced when low-level voltage applied to cartilage structure or graft initiates a series of oxidation-reduction reactions and alters distribution and content of electric charge associated with collagen-proteoglycan matrix and interstitial ionic solution [6].

EMR of flat cartilage grafts into semi-cylindrical or acute angular shapes have been demonstrated using surface and needle electrodes (Figure 1) [4, 5]. The degree of the shape change increases with increase in applied voltage or/and voltage application time until the reshaped graft conforms to geometry of reshaping apparatus [4-6]. At the same time, reshaping degree is directly related to electric charge transferred in the electric circuit during voltage application, confirming electro-chemical mechanism of EMR [6].
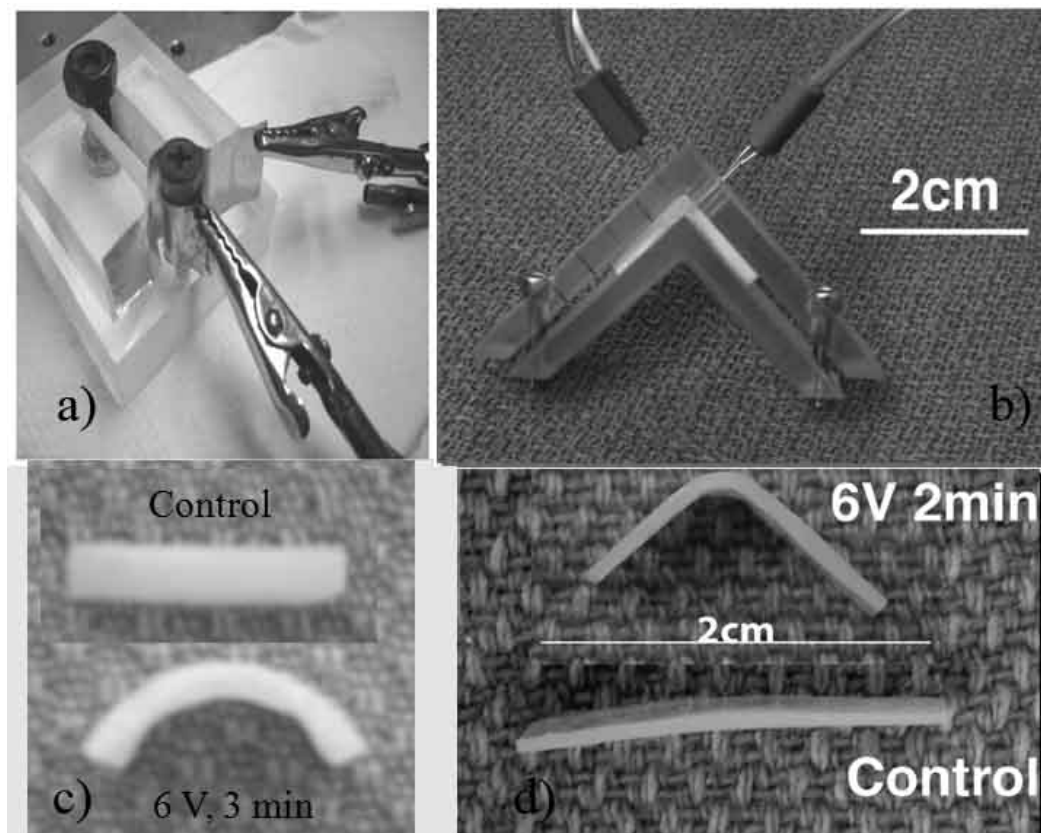

Figure 1: EMR of septal cartilage grafts: a) and c) reshaping of porcine cartilage into semicylindrical shape using gold surface electrodes [4], b) and d) reshaping of rabbit cartilage into 90 degree bend using platinum needle electrodes [5].

Simultaneously with the stress relaxation, EMR produces cartilage softening in the regions between the electrodes. Cartilage mechanical behavior can be best understood in terms of the triphasic theory (also known as the mechanoelectrochemical theory—MEC theory) [7]. This theory describes cartilage as a combination of solid collagen

framework, liquid water and electric charge distributed between solid and liquid phases. Polarized molecular groups (negatively charged SO_3^- and COO^-) are rigidly attached to collagen matrix and density of these fixed charges is known as fixed charge density (FCD). Ions (Na^{2+}, K^+, Cl^-) dissolved in cartilage water are free to move along pressure, concentration and electric gradients within cartilage. The interaction between fixed and free electric charges is one of the dominant factors determining cartilage mechanical properties [7, 8]. This study uses triphasic theory to describe the correlation between change in cartilage elastic modulus and electric charge transferred between electrodes during EMR. Characterizing EMR mechanical effect is an important step in understanding the physical processes responsible for reshaping and providing insight into how this procedure can be optimized.

2. MATERIALS AND METHODS

2.1 Experimental evaluation of cartilage during and after EMR

Porcine nasal septal cartilages were harvested from freshly killed pigs' crania obtained from a local abattoir (Clougherty Packing Company, Vernon, CA). Cartilage grafts from each septal cartilage were obtained and cut into uniform rectangular slabs (15x5x2 mm^3). The grafts were placed between two flat platinum electrodes and voltage varying from 0 to 8 Volts was applied to the electrodes. Voltage application time varied from 1 to 4 minutes. Electric current was recorded during voltage application and total electric charge transferred in electric circuit was calculated from integration of current traces as previously described [6]. Immediately following voltage application cartilage grafts were rehydrated in buffered saline solution for 15 minutes.

A 3 mm diameter biopsy punch was used to dissect a cylindrical section from the central portion of EMR treated cartilage grafts. Top and bottom of cylindrical samples were trimmed with a surgical razor to produce two parallel surfaces. The height of cylindrical samples was 1.6±0.2 mm. The samples were placed between two Teflon plates of mechanical testing platform (Bose Corp., Eden Prairie, MN) and compressive deformation (strain ε=0.1) was applied. A steady-state reaction force was recorded and sample elastic modulus was calculated.

2.2 Numerical implementation of triphasic theory

In triphasic mixture of cartilage four equations determine relationship between displacement of solid matrix, u, and fluxes of water, J^w, and positive and negative ions, J^+ and J^-, respectively [7, 9]. The equations are: mixture continuity

$$\nabla v^s + \nabla J^w = 0 , \tag{1}$$

where $v_s = du/dt$,

momentum conservation

$$\nabla \sigma = 0 , \tag{2}$$

where σ is the mixture stress tensor,

anion continuity:

$$\frac{\partial(\phi^w c^-)}{\partial t} + \nabla J^- + \nabla(\phi^w c^- v^s) = 0 , \tag{3}$$

where ϕ_w is cartilage porosity, c^- is anion concentration,

and cation continuity:

$$\frac{\partial\left(\phi^w c^+\right)}{\partial t} + \nabla J^+ + \nabla\left(\phi^w c^+ v^s\right) = 0,\qquad(4)$$

where c^+ is cation concentration.

The following boundary conditions written in cylindrical coordinate system were used:

at r=0:

$$u_r = 0,\qquad J_r^w = 0,\qquad J_r^+ = 0,\qquad J_r^- = 0,\qquad(5)$$

at r=a:

$$\sigma_{rr} = 0,\qquad(6)$$

where a=1.5 mm is the radius of cartilage sample

at z=0:

$$u_z = 0,\qquad J_z^w = 0,\qquad J_z^+ = 0,\qquad J_z^- = 0,\qquad(7)$$

and at z=h:

$$u_z = h\varepsilon(t),\qquad J_z^w = 0,\qquad J_z^+ = 0,\qquad J_z^- = 0\qquad(8)$$

where h=1.6 mm is the average height of cartilage sample.

Cartilage material properties and initial charge concentrations were taken from literature [9]. System of equations was solved using Comsol (COMSOL, Inc., Burlington, MA) software package.

3. RESULTS AND DISCUSSION

Simulation results of equilibrium reaction force, F, as a function of applied compressive strain are shown in Figure 2. Calculations were performed for various concentrations of negative charge in cartilage ranging from $c^-=c_0$, where $c_0=0.2$ mEq/ml is FCD in normal cartilage, to $c^-=0.01c_0$. Reaction force decreases with decrease in the negative charge concentration indicating that charged cartilage can support higher load than uncharged cartilage [7, 9]. The decrease in reaction force has almost linear dependence from charge concentration when the loss of the charge is moderate. Reduction of FCD by 50% results in approximately 50% reduction in reaction force. However, when the loss of electric charge becomes significant, the reaction force approaches saturation, indicating that only solid collagen matrix contributes to resisting deformation.
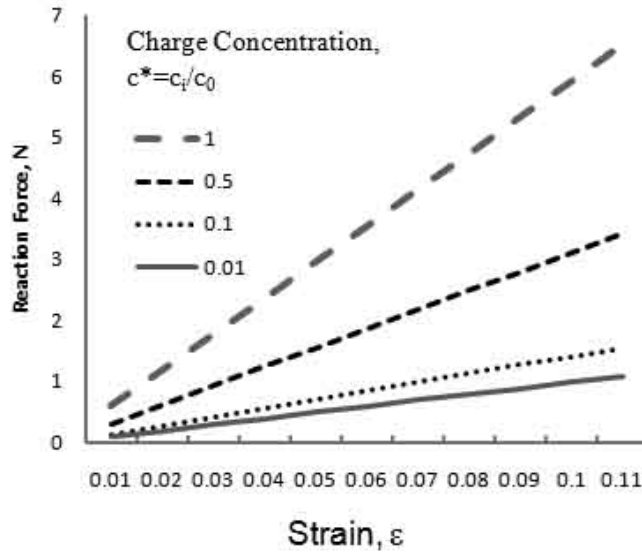
Figure 2: Equilibrium reaction force calculated as a function of applied compressive strain using triphasic theory. Calculations were performed for relative FCD ranging from 1 to 0.01 of FCD in native cartilage.

Figure 3 compares relative change in equilibrium elastic modulus after EMR calculated using triphasic theory and measured experimentally. The elastic modulus change is plotted as a function of relative loss of electric charge. For the charge losses of up to $0.5c_0$ triphasic theory predictions correlate well with experimentally observed decrease in elastic modulus. Higher charge loss produces saturation of elastic modulus observed in both experimental data and theoretical prediction. However, triphasic theory significantly underestimates maximal decrease in elastic modulus with complete loss of electric charge.
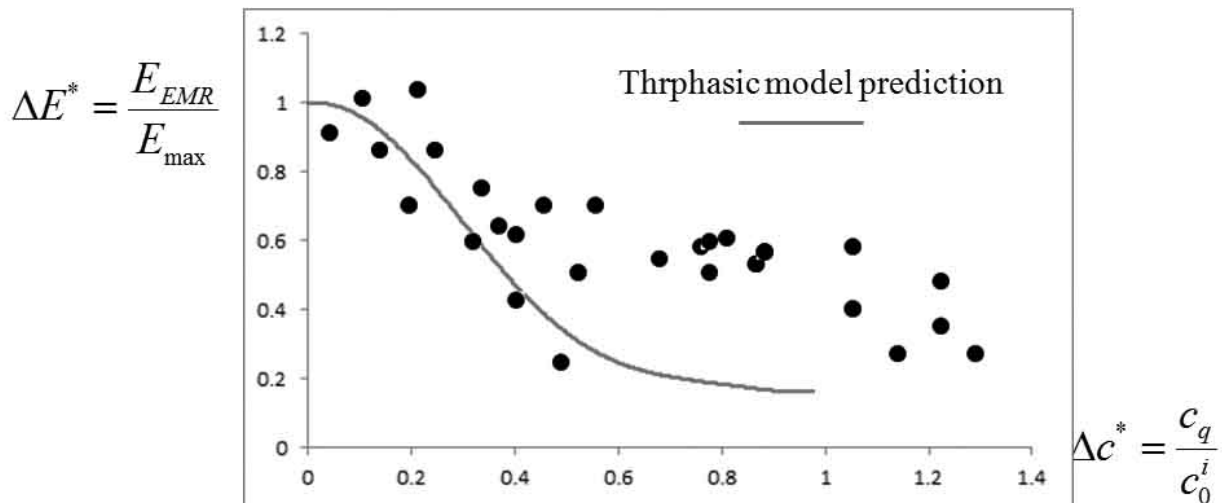

Figure 3: Relative change in equilibrium elastic modulus after EMR as a function of relative loss of electric charge during EMR

Good correlation of experimental data with theoretical predictions at low to moderate charge losses suggests that total electric charge transferred during EMR is a good approximation of depletion of fixed negative charges attached to collagen matrix. However, higher values of elastic modulus measured at the levels of transferred charge from $0.5c_0$ to $1.0c_0$, suggest that at high voltages and long application times the process of fixed charge depletion is either stopped or masked by production of additional charge in electrochemical reactions. The presence of additional charge is manifested by extension of experimental values of transferred charge beyond the level of the initial fixed charge (value of unity on x-axis in Figure 3).

It should be noted that saturation of changes in elastic modulus occurs at the same levels of electric charge transfer as saturation in reshaping degree observed in the previous studies [4-6]. Manual examination of cartilage grafts treated with voltages and application times that produce high level of charge transfer demonstrated significant change in cartilage color and texture, indicating deterioration of collagen matrix. However, further investigations, in particular observation of changes in cartilage dynamic mechanical properties following EMR, are required for complete understanding of EMR effect on cartilage mechanical behavior.

4. CONCLUSION

This study represents the first attempt to describe the changes in elastic modulus of septal cartilage grafts treated with EMR in terms of mechanoelectrochemical triphasic theory. Observed correlation between changes in elastic modulus predicted using triphasic theory and measured in experiment present a foundation for future studies of cartilage mechanical behavior during EMR. We plan to refine and expand our investigations on a range of electrical and mechanical properties as our interest in cartilage reshaping continues.

5. REFERENCES

1. Brent B. "Technical advances in ear reconstruction with autogenous rib cartilage grafts: personal experience with 1200 cases," *Plast Reconstr Surg*; 104, 319–334, 1999.

2. Lovice DB, Mingrone MD, Toriumi DM. "Grafts and implants in rhinoplasty and nasal reconstruction," Otolaryngol *ClinN Am*; 32, 113–141. 1999.

3. Helidonis E, Sobol E, Kavvalos G, Bizakis J, Christodoulou P, Velegrakis G, Segas J, Bagratashvili V., "Laser shaping of composite cartilage grafts," *Am J Otolaryngol*; 14(6), 410-2, 1993.

4. K.-H. K. Ho, S. H. Diaz, D. Protsenko, G. Aguilar, B. J. Wong, "Electromechanical reshaping of septal cartilage," *Laryngoscope*, 113(11), 1916-1921, 2003.

5. C. Manuel, A. Foulad, D. Protsenko, A. Sepehr, and B. J. Wong, "Needle Electrode Based Electromechanical Reshaping of Cartilage," *Annals of Biomedical Engineering*, 38(11), 3389-97, 2010.

6. D. Protsenko, K. Ho, B. Wong, "Stress Relaxation in Porcine Septal Cartilage during Elecromechanical Reshaping: Mechanical and Electrical Responses" *Annals of Biomedical Engineering*, 34(3), 455-64, 2006.

7. Sun, D. N., Gu, W. Y., Guo, X. E., Lai, W. M., and Mow, V. C., ''A Mixed Finite Element Formulation of Triphasic Mechano-Electrochemical Theory for Charged, Hydrated Biological Soft Tissues,'' *Int. J. Numer. Methods Eng*., 45, 1375–1402, 1999.

8. Maroudas, A., ''Physicochemical Properties of Cartilage in the Light of Ion Exchange Theory,'' *Biophys. J.*, 8(5), 575–595, 1968.

9. D. D. Sun, X. E. Guo, M. Likhitpanichkul, W. M. Lai, V. C. Mow, "The Influence of the Fixed Negative Charges on Mechanical and Electrical Behaviors of Articular Cartilage Under Unconfined Compression," *J. Biomech Eng.*,126(1), 6-16, 2004.

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