Using Optical Coherence Tomography to Monitor Effects of Electromechanical Reshaping in Septal Cartilage

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ABSTRACT

Electromechanical reshaping (EMR) of cartilage is a promising noninvasive technique with potential for broad application in reconstructive surgery. EMR involves applying direct current electrical fields to localized stress regions and initiating a series of oxidation-reduction reactions, thus effecting a shape change. Previous EMR studies have focused on macroscopic structural measurements of the shape change effect or monitoring of electrical current flow. Only limited investigation of structural changes in the tissue at the histologic level have been performed, and not in real time. This study is the first to use optical coherence tomography (OCT) to examine structural changes in cartilage during EMR. Two platinum needle electrodes were inserted into fixed rectangular rabbit nasal septal cartilage specimens. The spectral domain OCT probe was then positioned above the section of cartilage in which the anode needle was inserted. A constant voltage of 6V was applied for 3 minutes, and images were obtained (8 frames/second). OCT was also performed in specimens undergoing dehydration under ambient conditions and during pH changes produced by the addition of HCl, as both processes accompany EMR. The OCT data identified distinct findings among the three conditions, suggesting that EMR causes a much greater degree of reshaping on a molecular level than dehydration or a change in pH alone. OCT provides a means to gauge structural changes in the tissue matrix during EMR. The application of OCT to image the EMR process will add to our understanding of the mechanisms of action involved and potentially facilitate optimization of this process.

Keywords: electromechanical, reshaping, cartilage, optical coherence tomography, reconstructive surgery

1. INTRODUCTION

Cartilage reshaping is a key element in facial reconstructive surgery. Cartilage tissue is used to provide structural support for soft tissues in the head, neck, and upper airway, as well as support for joint movement.[1] Surgical techniques have been developed to reshape cartilage to replace damaged or missing cartilage due to trauma, surgical defects, or congenital malformations. Conventional techniques include sculpting, morselizing, or suturing grafts from native cartilage.[2] However, these techniques are complex and invasive, and results often depend on the skill of the surgeon. Current procedures also come with risks such as warping of cartilage over time and graft rejection. Alternative procedures such as thermal-dependent laser and radiofrequency cartilage reshaping have been proposed.[3,4]

Electromechanical reshaping (EMR), or electroforming, is a novel method for cartilage reshaping in which a DC electric field is applied to cartilage specimen mechanically fixed in a jig, effecting long-lasting change in cartilage shape. [1,5,6] EMR is non-invasive, and unlike laser and radiofrequency techniques, it is not thermally dependent.[1] Previous studies have proposed an electromechanical mechanism to explain the shape change that occurs during EMR.[5] As shown in Figure 1, a series of oxidation-reduction reactions combined with a change in the distribution of proteoglycans in the tissue matrix due to protein electrophoresis are believed to be the chemical mechanisms behind the shape change observed. Previous studies found the mechanical stability of reshaped EMR samples to be similar to that of native cartilage tissue, and that shape retention after EMR is proportional to increasing voltage applied and application time.[5]

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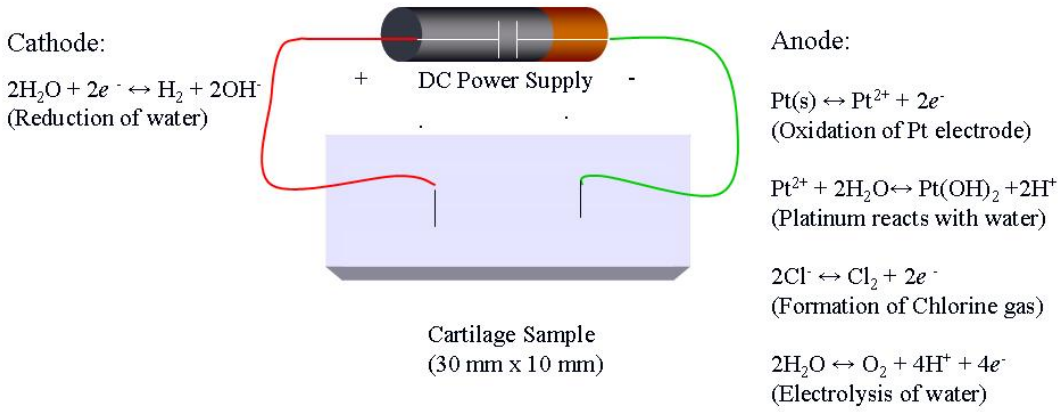

Figure 1. Schematic of proposed oxidation-reduction reactions occurring during electromechanical reshaping. At the cathode, hydrolysis of water results in platinum deposition and hydrogen gas formation. At the anode, several oxidation reactions lead to chlorine and oxygen gas formation.

While preceding studies have taken structural measurements of shape change and retention at the macroscopic level, few studies have observed structural changes in tissue at the histological level. Histological slides have been created from samples of cartilage before and after voltage is applied, but these images cannot capture the structural change occurring throughout the duration of the EMR process. This study is the first to observe structural change at a histological level during the EMR process using optical coherence tomography (OCT). OCT is an emerging technology that allows for high-resolution cross sectional micron scale imaging of biological tissues.[7] Unlike histology, OCT is a noninvasive scanning system that can provide real-time images at a rapid pace (8 frames/sec) while voltage is applied to the cartilage.

2. METHODOLOGY

2.1 Specimen Preparation and EMR Setup

Rabbit septal cartilage was harvested from New Zealand White Rabbits obtained from a local abattoir (Rabbit Farm, Turlock, CA). Cartilage grafts were obtained from the cranial region and sliced into uniform rectangular slabs approximately 30 mm x 10 mm x 1 mm. Cartilage samples underwent three different treatments: dehydration under ambient conditions, which served as a control; a drop-wise addition of 0.5 M HCl to simulate the pH change that accompanies EMR; and EMR with an application of 6 V over 180 seconds. Before EMR application, tissue was kept hydrated in 1x phosphate buffered saline solution without calcium or magnesium (PBS, pH 7.4, Sigma-Aldrich).

2.2 Optical Coherence Tomography Setup

A spectral domain OCT system was used to monitor shape change (see Figure 2). A beam of infrared light is directed onto the tissue, and microstructures at different depths within the tissue scatter light.[8] The intensity and phase of the backscattered light are measured and compared to yield images at a frame rate ranging from 7 to 20 frames at an A-line speed of 47 kHz. OCT images were obtained at a rate of approximately 8 frames per second to maintain a high pixel resolution of 1024x512.

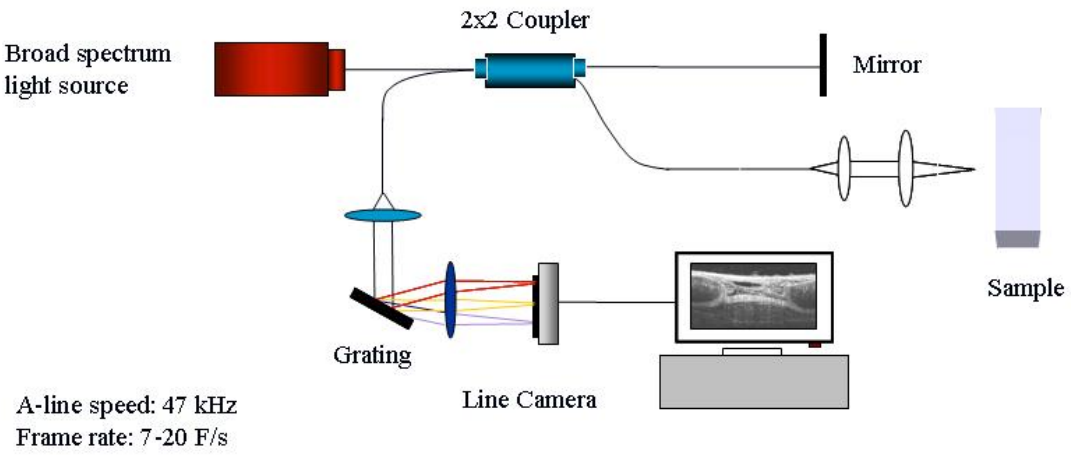

Figure 2. Spectral Domain OCT System

2.3 Integration of OCT and EMR Systems

The rectangular cartilage sample was wedged into a 2 mm wide, shallow slit cut into a rectangular styrofoam block in such a fashion that the specimen was fixed perpendicular to the block's surface (see Figure 2). While the purpose of EMR is to effect shape change, the cartilage was not mechanically bent into a jig as performed in previous EMR experiments, as the main objective of the study is to visually examine structural changes at a histological level. Instead, the cartilage remained fixed in a linear shape so that the OCT system could scan in a back-and-forth linear motion to obtain visual information on cells in the vertical plane parallel to the sample's lengthwise alignment.

Two platinum electrode needles were inserted into the cartilage at points 1-2 mm below the surface and 20 mm apart from each other. The OCT probe was placed directly above the insertion point of the anode. A battery pack consisting of four 1.5 V alkaline AA batteries was used as an external voltage source which delivered 6 V in 180 seconds. To monitor the voltage delivered throughout each trial, a voltmeter was connected to the batteries. 1500 frames were recorded for the duration of each 180 second trial. This recording procedure was repeated for samples under ambient conditions (natural dehydration) and addition of 100 µL 0.5 M HCl. Each trial's frames were then compiled into a video file for comparison and analysis.

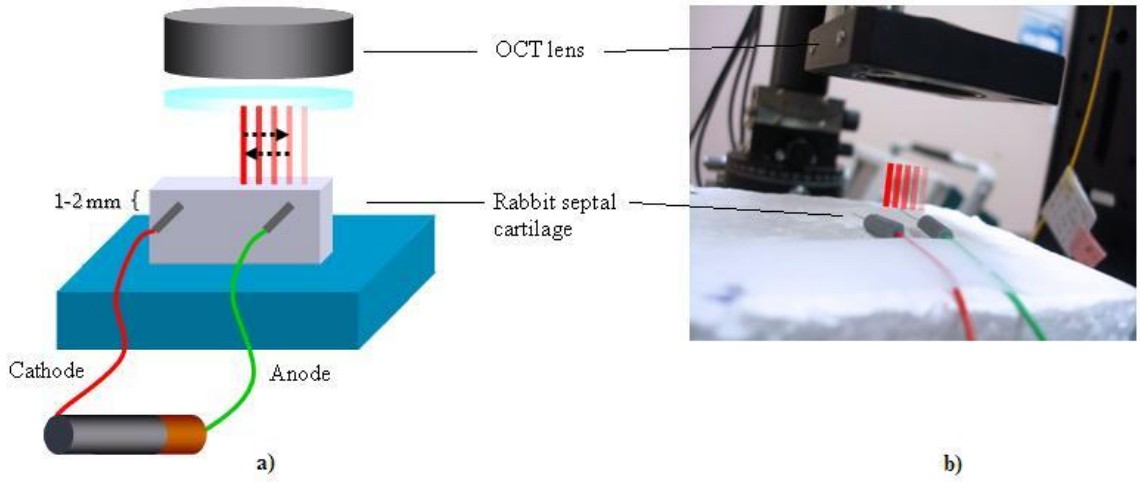

Figure 3. Integration of OCT with EMR apparatus. A schematic diagram is shown on the left in a), while the actual setup is shown in b). Red bars indicate the sweeping motion of the OCT probe.

3. RESULTS

Figure 4 compares images from trials in which specimen were either observed under natural dehydration, addition of HCl, or EMR. Four different frames were selected to represent different time points in the EMR process, with Frame 0001 at 0 seconds before EMR was applied, followed by Frame 0501 at 60 seconds into the voltage application, Frame 1001 at 120 seconds, and Frame 1501 at 180 seconds, right after voltage application has terminated.

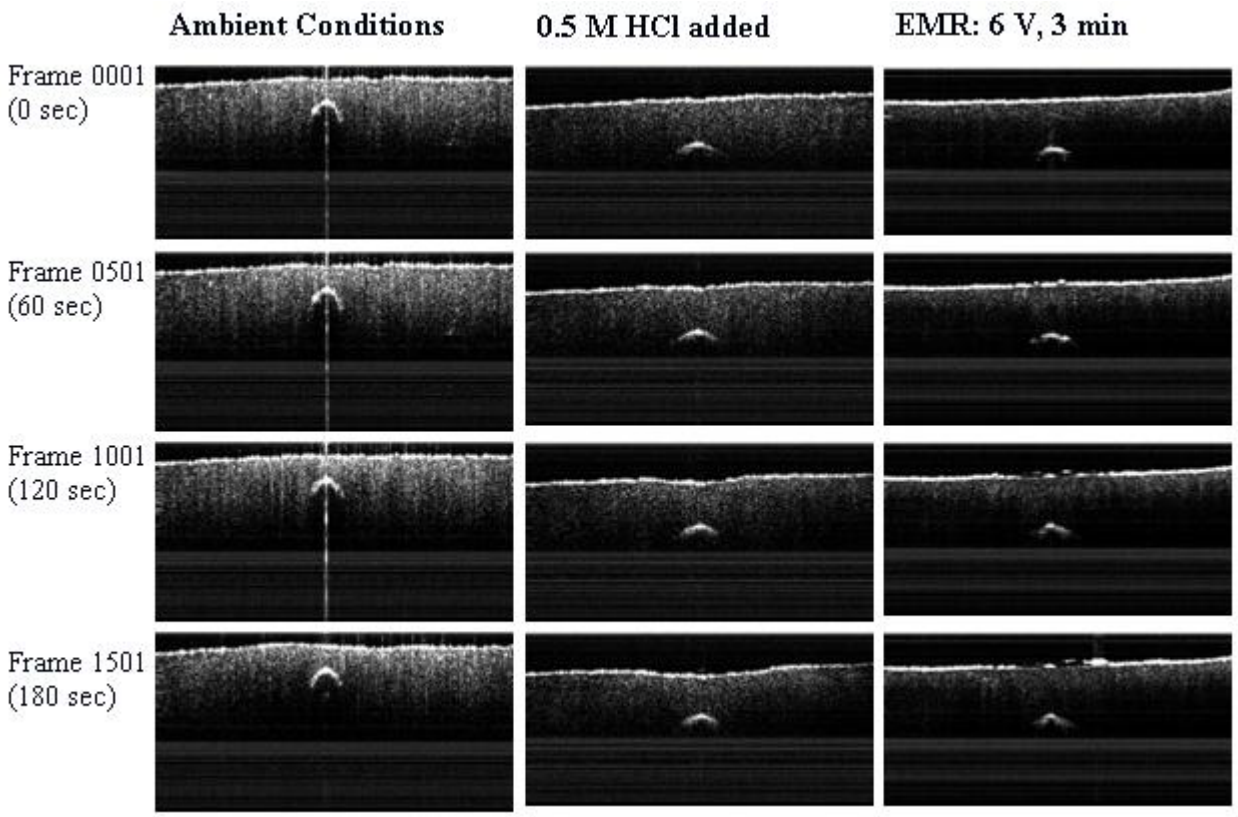

Figure 4. Frames of OCT images from three separate treatments: natural dehydration (control), simulated pH change, and EMR application. For each treatment, approximately 1500 frames were collected over 180 seconds. The four frames shown here represent intermediate phases in the experiment at 60 second time intervals.

4. DISCUSSION AND CONCLUSION

The OCT data identified distinct findings among the three conditions, suggesting that EMR causes a much greater degree of reshaping on a molecular level than dehydration or a change in pH alone. While a change in pH showed more significant compositional change than natural dehydration, OCT-EMR results indicate an even more dramatic change in surface structure and composition. In the OCT-EMR video, a significant degree of reshaping, cell migration and bubble formation are observed in concentric rings radiating out from the anode. It is possible that the OCT images of EMR samples are capturing the migration of negatively charged proteoglycan molecules from the anode to the cathode. These results reinforce the results of previous studies which suggest that water hydrolysis and electroforming are the electromechanical mechanisms behind shape change and retention.

This experiment has proven that OCT is an appropriate tool that can be used to gauge structural changes in the tissue matrix during EMR. More samples must be monitored with varying EMR and OCT parameters to draw further conclusions as to the specific mechanisms causing shape change at the histological level. However, by using OCT to monitor structural changes during EMR, this study has further contributed to our understanding of the electrochemical reactions behind the process, and serves to highlight EMR's potential as a non-invasive clinical technique.

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