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Cartilage Reshaping: An Overview of the State of the Art

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ABSTRACT

The laser irradiation of cartilage results in a plastic deformation of the tissue allowing for the creation of new stable shapes. During photothermal stimulation, mechanically deformed cartilage undergoes a temperature dependent phase transition, which results in accelerated stress relaxation of the tissue matrix. Cartilage specimens thus reshaped can be used to recreate the underlying framework of structures in the head and neck. Optimization of this process has required an understanding of the biophysical processes accompanying reshaping and also determination of the laser dosimetry parameters, which maintain graft viability. Extensive in vitro, ex-vivo, and in vivo animal investigations, as well as human trials, have been conducted. This technology is now in use to correct septal deviations in an office-based setting. While the emphasis of clinical investigation has focused on septoplasty procedures, laser mediated cartilage reshaping may have application in surgical procedures involving the trachea, laryngeal framework, external ear, and nasal tip. Future directions for research and device design are discussed.

Keywords: Cartilage, Laser Mediated Cartilage Reshaping, Stress Relaxation, Otolaryngology, Plastic Surgery, Phase Transformations

1.0 INTRODUCTION

Cartilage is a dense connective tissue, best described as a gel of non-diffusible macromolecules reinforced by collagen fibers. Cartilage is composed of 60 -80% water and a small volume fraction of cells (chondrocytes) within the extracellular matrix. Cartilage provides structural support for many structures in the head and neck and forms the articular surfaces in load bearing joints. In the head and neck, disease, congenital malformation, traumatic injury or a blative surgery may alter the morphology of these structures resulting in functional deficits. Reconstruction (carving, morselizing, scoring, or suturing) of cartilaginous defects often require the use non-vascularized cartilage autografts. The limitations of these techniques result from the potential donor site morbidity that occurs during tissue harvest, as well as the inability to appropriately accommodate the donor graft to the geometric constraints of the recipient site. Although a variety of treatment strategies have been proposed for the regeneration or repair of diseased and deformed cartilage, the development of an alternative method to alter cartilage shape without surgery has until recently remained elusive.

In 1993, Emil Sobol introduced a novel method of reshaping cartilage using non-ablative laser irradiation to accelerate mechanical stress relaxation and permanently modify graft shape¹. A growing body of basic and clinical data supports the use of this new technology for potential therapy for diseased cartilage and anatomical defects. In this review, we will discuss the biophysical process involved in laser-mediated cartilage reshaping and summarize the current clinical experience of this technology.

1.1 Biophysical Process

Cartilage resists deformation due to the molecular forces generated between water and proteoglycan molecules, which balance the applied load. Focal irradiation to regions of the cartilage specimen where maximum stress is distributed leads to stress relaxation and shape change (Figure 1).

Figure 1. Illustration of the laser reshaping process: (A) Mechanically deformed cartilage; (B) Laser irradiation; (3) Stable shape change.

Measurements of tissue optical, mechanical, and thermal properties during photothermal heating identified characteristic changes in tissue properties that occurred within a critical temperature range of 60 -70°C²⁻¹⁴. Real-time internal stress measurements indicate that when cartilage reaches this temperature, mechanical stress relaxation occurs⁸. The onset of accelerated stress relaxation also corresponds to the observation of a peak in diffusely reflected light from a visible wavelength probe laser⁷. These real-time indices have been used to control the laser reshaping of cartilage tissue¹⁰, maintaining tissue temperatures below the threshold for protein denaturation (70°C). However, precise control of the temporal and spatial aspects of the heating process remains a challenge.

Studies published by Sviridov and others indicate that a “therapeutic window” for effective reshaping exists between laser fluence and irradiation time⁹. This “window” will vary with tissue thickness and laser wavelength. Insufficient energy or laser exposure time results in inadequate shape change without significant alteration of the extracellular matrix, while overheating will create stable shapes, but may result in significant thermal injury (Figure 2). To optimize laser mediated cartilage reshaping, the heating process must be precisely controlled, as loss of chondrocyte viability may result in complete graft resorption, infection, and/or necrosis. Recent studies have indicated that chondrocyte viability decreases with prolonged or repeated laser irradiation¹⁵.

Figure 2. Representation of the optimal laser parameters for effective cartilage reshaping.

1.3 Mechanism of Action

Though the precise mechanism of action of laser-assisted reshaping is still under investigation, the process is likely dependent on a temperature (70°C) sensitive bound-to-free water phase transition. Sobol and others have postulated that under moderate laser heating, internal stress relaxation occurs when water bound to the proteoglycans is liberated. If this process occurs without damaging the matrix macromolecules then stable shape change occurs. Several phenomenological mechanisms have been proposed to account for reshaping¹⁶: (1) local mineralization of the proteoglycans negative charges by Na^{+} and Ca^{+} cations occurs without altering the collagen and proteoglycan microstructure; (2) temperature dependent depolymerization of proteoglycan aggregates followed by a re-formation of the proteoglycan structure without significant denaturation of the extracellular matrix; and (3) short-time disruption of bonds between the collagen and proteoglycan subunits, facilitating a decrease in internal stress by altering the spatial structure of the proteoglycans. Indirect supportive evidence for the first two theories were gained by Sobol et al (1999) with the aid of AFM and light scattering techniques measurements¹⁷. Following 30 seconds of irradiation from a CO_2 laser, small (submicron) crystals form within the irradiation zone. These have subsequently been found to consist of sodium carbonate and calcium carbonate, which may contribute to both short-term and long-term stability, respectively. Further molecular and chemical studies will continue to provide important information on the underpinnings of the mechanism of action.

1.4 Graft Shaping Techniques

Cartilage can be reshaped using either diffuse or focal irradiation. Using diffuse laser irradiation, the entire specimen is heated (bulk heating) using relatively low power densities to create gently curved shape changes in the tissue (Figure 3a). Ex vivo experiments have shown that though shape change occurs, there is some degree of shape memory that may result in the reduction of curvature (Figure 4). To compensate for this effect, the graft must be "over-bent" during reshaping so that the target configuration is attained after stabilization.

Figure 3. Illustration of Diffuse (A) and Focal (B) Irradiation techniques used to reshape cartilage.

Using focal laser irradiation, the regions of maximum stress (in a deformed specimen) are irradiated using relatively high power densities in order to reshape cartilage with relatively acute angles (Figure 3b). This approach has been used clinically to correct nasal septal defects (see below), and in animal studies to reshape ears and crushed tracheal rings. Despite clinical implementation and several *in vivo* studies (see below) cellular viability following this intense photothermal interaction has not been determined using vigorous techniques.

Figure 4. Schematic representation of the "memory effect" following laser reshaping.

1.5 *In Vivo* and Clinical Studies

The first reported clinical studies (three patients) were performed in Crete in 1992, by E. Helidonis and colleagues¹, who removed segments of deformed nasal septal cartilage, straightened using CO₂ laser irradiation, and then re-implanted the grafts in their normal anatomic position. This prompted a series of animal experiments, as the precise laser dosimetry accounting for the phenomena was unknown.

In 1994 V. Ovchinnikov et al, in Russia used a CO₂ and holmium laser to reshape the auricular cartilage of five rabbits (*in vivo*)¹⁸. In 1995, Z. Wang (United States), used a 1.44 μ m laser to reshape the collapsed tracheal rings of three dogs¹⁹. Between 1997 (Ovchinnikov et al, Russia) and 1998 (Jones et al, United Kingdom) two studies were conducted to assess the long-term results after laser reshaping of ear cartilage from seventeen pigs using a holmium laser.

In 1998, Ovchinnikov and coworkers (Russia), began using a holmium laser to correct nasal-septal defects (septoplasty). In conventional septoplasty surgery, the procedure is performed in the operating suite under general anesthesia. Post-operative complications include bleeding, pain, infection and the usual risks of anesthesia, with recovery often taking several weeks. With laser-assisted septoplasty, the procedure is done in the office using aerosolized local anesthesia. A double-pronged metal spreader, specifically designed for this application, is placed within the affected nasal airway. The obstructing septal cartilage is pushed medially to open the airway. An optical wire is introduced intranasally and the cartilage is irradiated (6-8s pulses) from the cephalic to caudal end. The spreading apparatus is removed from the nostril and replaced by a cotton pledget. The optical fiber is then placed into the unaffected nostril and used to irradiate the newly reshaped cartilage from the opposite side. This painless and bloodless procedure takes ten minutes to complete. E. Sobol and colleagues (2000) reported results of a study incorporating 40 patients²⁰. Rhino-gastrometrical examinations before and at 6 months following laser reshaping indicate significant improvement in the nasal airflow of 32 of the 40 patients. Six of the eight non-responders benefited from retreatment using a higher fluence. Post-operative fiberoptic nasal endoscopy illustrates a marked and stable increase in the nasal airway patency.

2.0 CONCLUSIONS

The growing body of evidence thus far clearly illustrates the potential impact of laser-assisted shaping in surgery involving cartilaginous structures. Studies are currently under way to better understand the photothermal effects on chondrocytes, develop biophysical models, and elucidate the mechanism of action of laser reshaping. Optimization of laser dosimetry, development of clinical instrumentation, and further clinical trials are areas requiring further investigation. Data from these studies will no doubt further refine our efforts toward making this novel technique a clinical procedure with many applications in the fields of Otolaryngology, Orthopedics, and Plastic/Reconstructive Surgery.

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