Laser mediated cartilage reshaping

Wong, B.J.F.

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Feedback-Controlled Laser-Mediated Cartilage Reshaping

Brian J. F. Wong, MD; Thomas E. Milner, PhD; Andrew Harrington; Jason Ro; Xavier Dao; Emil N. Sobol, PhD; J. Stuart Nelson, MD, PhD

Objective: To demonstrate feedback-controlled laser-mediated cartilage reshaping using dynamic measurements of tissue optical properties and radiometric surface temperatures.

Design: Flat cartilage specimens were reshaped into curved configurations using a feedback-controlled laser device.

Materials: Fresh porcine nasal septum, stripped of perichondrium and cut into uniform strips (25 X 10 X 1.5-2.1 mm) with a custom guillotine microtome.

Interventions: Cartilage specimens secured in a cylindrical reshaping jig (2.5 cm in diameter) and irradiated with an Nd:YAG laser (λ = 1.32 μm, 25 W/cm², 50-Hz pulse repetition rate). During laser irradiation, radiometric surface temperature was measured along with changes in forward-scattered light from a diode probe laser (λ = 650 nm, 5 mW), using a lock-in detection technique. Sequential irradiation of the specimen outer surface was made (3 laser passes). Characteristic changes in tissue temperature and light-scattering signals were used to terminate laser irradiation.

Results: Effective reshaping was accomplished for both thin (1.5-mm) and thick (2.1-mm) specimens. Following reshaping, specimens were stored in saline solution at 4°C for 21 days. No return to the original flat configuration was noted during this period.

Conclusions: The prototype device effectively reshapes flat native porcine cartilage into curve configurations. The use of optical and thermal signals provides effective feedback control for optimizing the reshaping process.

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During laser irradiation, mechanically deformed cartilage undergoes a temperature-dependent phase transformation that results in accelerated stress relaxation. As a consequence, laser-irradiated cartilage may be molded into complex new shapes that remain stable as the tissue cools without the need for suturing, scoring, or morselization to relieve and/or balance the intrinsic elastic forces that resist deformation. The principal advantages of using laser radiation for the generation of thermal energy in tissue are precise control of both the space-time temperature distribution and time-dependent thermal denaturation kinetics.

We illustrate the reshaping process schematically in Figure 1. A flat cartilage specimen (Figure 1, A) is maintained in user-defined mechanical configuration by a jig (Figure 1, B) and then irradiated with a laser. Following cessation of laser irradiation, the specimen (and jig) is immersed in saline solution at 20°C for 15 minutes. The jig is removed and a stable shape change is achieved (Figure 1, C). The optimization of laser-mediated reshaping requires precise control of the time-dependent heating profile in cartilage during radiation. Cartilage reshaping (stress relaxation) occurs when the tissue reaches a critical temperature transition range and remains within this region for a minimum time interval. If the cartilage tissue remains at elevated temperatures for a prolonged period, cell death and tissue necrosis will result. Effective shape change occurs when the temperature change is adequate to reshape the cartilage without causing nonspecific chondrocyte apoptosis. Our preliminary studies indicated that reshaping can be accomplished without significant loss of chondrocyte viability, but laser dosimetry must be precisely controlled to minimize nonspecific thermal injury.

Feedback control of the reshaping process requires a real-time technique to monitor dynamic changes in the physical properties of laser-irradiated cartilage.
MATERIAL AND METHODS

Nasal septal cartilage was extracted from freshly euthanized pigs obtained from a regional abattoir (Cloughbery Packing Company, Vernon, Calif) and cut into slabs (25 x 10 mm) of uniform thickness varying from 1.3 to 2.1 mm using a custom guillotine microtome. The cartilage specimens were secured to an inner cylindrical wireframe jig (2.5 cm in diameter) with an outer hemicylindrical retaining frame and held in mechanical deformation (Figure 3). The jig was constructed from fencing wire (0.6 cm [0.25 in] square size), which allowed maximal exposure of the cartilage specimen to incident laser irradiation while still maintaining secure and stable mechanical deformation. Light from an Nd:YAG laser (A = 1.32 µm, 50 Hz pulse repetition rate) (New Star Lasers, Auburn, Calif) was delivered via a multimode low hydroxide silica optical fiber terminated with an anti-reflection-coated collimating lens. The fiber delivery system was combined with a thermopile detector (response time of 120 milliseconds [95%]; spectral sensitivity, 7.6-18 µm) in a single unit (New Star Lasers) (Figure 4). The thermopile detected infrared emissions from a source area on the cartilage surface 3 mm in diameter. Calibration was performed as previously described and S(t) was calculated.15 Laser spot size (5.4 mm in diameter) was measured with thermal paper (Zap-it; Kentek, Pittsfield, NH). Laser power density (25 W/cm²) was measured with a pyroelectric meter (Model 10A-P; Ophir Optronics, Jerusalem, Israel).

A diode probe laser (λ = 650 nm, 5 mW) (MWK Industries, Corona, Calif) was directed perpendicularly onto the irradiated surface of the cartilage specimen and centered within the laser spot produced by the Nd:YAG laser.12 A mechanical chopper (Model R540; Stanford Research Systems, Sunnyvale, Calif) was used to amplitude modulate (600 Hz) the intensity of the diode laser. Forward-scattered light from the diode laser was focused by a condenser lens (numerical aperture of 0.5, 86 mm in diameter; MWK Industries) into an integrating sphere (15-cm [6-in] diameter, IS-060; Labsphere, North Sutton, NH) and synchronously detected using a silicon photoreceiver (Model 2001; New Focus, Mountain View, Calif) and a lock-in amplifier (time, 100 milliseconds) (Model S8800; Stanford Research Systems) to give integrated forward-scattered light intensity (I(f(t))). Data were acquired using a 16-bit AD converter (AT-MIO-16XE-50; National Instruments, Austin, Tex) and a personal computer (Equicomp Solutions, Westminister, Calif) running software written in LabView (version 5.0; National Instruments).

The cartilage and reshaping jig were secured to a computer-controlled positioning device (Lego Dacta, Pittsburg, Kan), which rotated or linearly translated the specimen relative to the fixed laser beam in stepwise increments, and hence permitted sequential irradiation of the entire specimen outer surface. Laser irradiation was terminated at each site on the specimen when either S(t) reached a user-defined end point (70°C) or when I(f(t)) reached an absolute minimum. The positioning device, laser power, and temperature-light-scattering analysis algorithms were controlled by a "virtual instrument" programmed in LabView, with software designed to detect both temperature thresholds and minima in the light-scattering signal. The entire outer surface of the cartilage specimen could be irradiated with multiple laser passes over the same region. In general, repeated laser irradiation (on a given region) results in more pronounced shape changes and sustained stress relaxation; however, repeated irradiation decreases chondrocyte viability. Three laser passes were used, as effective reshaping can be achieved without compromising chondrocyte viability significantly.17

Immediately following laser irradiation, the cartilage specimen was removed from the jig and secured to a smaller frame-wire jig (1-1.5 cm in diameter) of similar construction. The specimen and jig were immersed in saline solution at ambient temperatures for 15 minutes to allow dehydration. The specimen was removed from the jig and stored in saline solution at 4°C for 21 days. Specimens were photographed before, during, and after reshaping at various time intervals.

Changes in optical, thermal, and mechanical properties of cartilage accompanying the laser-mediated reshaping may be dynamically monitored by measuring scattered-light intensity (from a probe laser), radiometric surface temperature (S(t),[t]), heat capacity, and internal stress in real time.10,11,12 Infrared radiometry relies on the measurement of blackbody radiative emissions, resulting from temperature elevations created by absorption of laser radiation. Spectral radiance of blackbody emissions from the cartilage surface is a function of tissue emissivity and temperature and is described by the Planck radiation law: the detected radiometric signal contains information concerning the optical and thermal properties of the cartilage. Thermopiles or solid-state infrared detectors can be used to measure the increased blackbody emission and, when properly configured and calibrated, surface temperature can be estimated. As photo-thermal heating produces alterations in the fine structure of the specimen (eg, protein structure, water content), tissue optical properties also undergo dynamic change that can be measured using a second probe laser beam (at a visible wavelength) centered on the heated region. Intensity of diffusely scattered light (forward scattered or backscattered) results from real-time changes in tissue optical properties (primarily tissue-scattering coefficients for visible laser wavelengths in cartilage).10,17

When a mechanically deformed cartilage specimen is irradiated with laser energy, internal stress initially increases, plateaus, and then rapidly decreases (stress relaxation) (Figure 2, A). Temperature-sensitive tensiometric measurements of cartilage internal stress during laser irradiation suggest that marked stress relaxation occurs when tissue temperature reaches approximately 60°C to 70°C.5,13 In this temperature range, a slope change (arrow) in the heating curve is also observed, suggesting a change in tissue thermal properties (Figure 2, B). As the tissue is heated, the same molecular alterations in tissue matrix structure that result in reshaping also cause changes in tissue optical properties and may be determined by measuring either forward-scattered or backscattered light from a second probe laser (at a visible wavelength such as 650 nm) (Figure 2, C). The onset of stress relaxation, a local
extremum in the light-scattering signal, and slope change in the radiometric temperature occur simultaneously. Noncontact optical and radiometric measurements may be used to infer changes in cartilage mechanical properties, and hence be used to modulate laser energy and feedback control the reshaping process, and form the basis for our design and construction of a prototype closed-loop feedback-controlled device to reshape cartilage using real-time measurements of tissue temperature and alterations in optical properties.

**RESULTS**

**Figure 5** is a photographic montage of a cartilage specimen (2.1 mm × 25 mm × 10 mm) undergoing reshaping. Figure 5, A, the cartilage specimen before reshaping; Figure 5, B, during laser irradiation (secured in the reshaping jig); Figure 5, C, immediately after laser irradiation; and Figure 5, D, the same specimen following 15 minutes of rehydration in normal saline solution (while wrapped around a jig of smaller diameter). Measurements of $I_0(t)$ and $S_0(t)$ were used to terminate laser irradiation. The entire outer surface of the specimen (secured within the jig, Figure 3) was irradiated 3 times. Consistent with prior observations, specimen morphology did not change during a 3-week time interval. Similar findings were observed in experiments involving thinner cartilage specimens.

**COMMENT**

The interaction of coherent light with tissue may result in a variety of effects depending on the laser wavelength, pulse duration, irradiance, and tissue thermal and
Figure 4. Schematic of prototype closed-loop feedback-controlled device for laser-mediated cartilage reshaping.

Figure 5. Reshaped cartilage specimen: A, prior to irradiation; B, specimen in reshaping jig secured to device; C, specimen immediately following reshaping; and D, specimen after 15 minutes of rehydration.
optical properties. In industry, photothermal, photomechanical, and photochemical effects are used for ablative and nonablative applications in many areas, such as semiconductor, alloy, ceramic, and polymer processing. While industrial nonablative laser applications are commonplace, lasers have been used predominantly in medicine to ablate or photocoagulate tissue. Few nonablative uses of lasers exist in medicine, and laser-mediated reshaping of cartilage is a novel application. Laser interactions in cartilage result in thermal-mediated alterations in cartilage biophysical properties, strongly suggesting the occurrence of a phase transformation. In cartilage, these energy-dependent changes in molecular structure are manifest by alterations in the tissue matrix. Preliminary investigations have determined the optical, thermodynamic, and mechanical changes in cartilage tissue in response to laser irradiation, and the critical temperature regions in which they occur, although the molecular basis for thermal-mediated stress relaxation remains incompletely understood. We have used these findings to develop a prototype device to reshape cartilage tissue using dynamic measurements of $S(t)$ and alterations in tissue optical properties.

Figure 5 illustrates the modification of a thick (2.1 mm) cartilage specimen from a flat to a curved shape. Specimen shape was determined by the reshaping jig, which provides sustained mechanical deformation during laser exposure. A simple curve was selected for these initial studies, though other geometries can be attained by altering the jig shape and modifying the software-controlling specimen translation. The device used dynamic measurements of tissue light-scattering properties and surface temperature to control the reshaping process. The changes in forward-scattered light signal $I_0(t)$ are small (on the order of 9%), and, without a lock-in detection method, difficult to observe in the presence of noise from ambient lighting and display panel sources. With appropriate amplification technique, changes in tissue optical properties are quite dramatic and easily identified. However, detecting absolute minima in $I_0(t)$ is challenging when the specimen and/or jig moves or shifts during laser irradiation, or when the probe laser beam is blocked or partially reflected by the wire frame of the reshaping jig. As a fail-safe measure, $S(t)$ measurements were used to prevent overheating of the specimen, and laser irradiation was terminated if surface temperature reached 70°C. Cartilage undergoes accelerated stress relaxation near 70°C, though the critical temperature is dependent on the rate of temperature change. The requirement for a fail-safe approach is extremely critical for specimens irradiated with multiple passes of the laser, as the characteristic minimum in $I_0(t)$ becomes increasingly difficult to observe.

Three laser-mediated cartilage reshaping studies have been performed in animals, though none of these investigations monitored changes in tissue temperature, optical properties, or internal stress or was a feedback control system used to modulate laser dosimetry. Laser-mediated cartilage reshaping is undergoing clinical trial in septoplasty operations in Russia; to date, 33 patients have undergone laser surgery (without feedback control) using a Ho:YAG laser ($\lambda = 2.12 \mu m$) without near-term morbidity. Furthermore, this technology may be adapted for use with minimally invasive techniques to reshape cartilage in regions difficult to access such as the trachea. While laser reshaping of relatively thick cartilage specimens was demonstrated in this study, the device works equally well with thinner specimens, which would likely be encountered in the nasal tip, septum, and trachea.

### CONCLUSION

Laser-mediated cartilage reshaping relies on temperature-dependent accelerated stress relaxation. The therapeutic interval between adequate shape change and overt chondrocyte death is narrow, and a real-time method to access alterations in tissue physical properties during laser irradiation is required. We have constructed a device using noncontact optical and radiometric techniques to monitor changes in tissue biophysical properties and used these to feedback control the reshaping process and minimize uncontrolled heating. Cartilage may be heated in a controlled manner to the point where accelerated stress relaxation occurs, well below the threshold for thermal necrosis. If properly developed and carefully implemented, feedback-controlled laser-mediated cartilage reshaping may radically alter the practice of head and neck reconstructive surgery. The treatment of prolaberent lop ears, nasal deformities, laryngeal crush injuries, and tracheal deformity could be improved using laser-based devices, without the attendant donor site morbidity or irreversibility associated with traditional reconstructive techniques. We plan to pursue animal studies and clinical trials using further modifications of the prototype device described in this study.

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Reprints: Brian J. F. Wong, MD, Beckman Laser Institute and Medical Clinic, University of California, Irvine, 1002 Health Sciences Rd E, Irvine, CA 92612 (e-mail: bjfwong@bli.uci.edu).

### REFERENCES

The 2 False Assumptions of a Traditional Rhinoplasty Model

Two assumptions underlie the logic of the “skeletal reduction, soft tissue contraction,” neither of which may be valid in many clinical situations.

Assumption 1: The nasal soft tissue cover has an infinite ability to contract to the shape of the underlying skeleton. To a limited degree (depending upon the quality, thickness, and distribution of the preoperative skin sleeve), nasal skin will shrink, but not necessarily to the shape of the underlying skeleton (which may be contracting itself.)

Assumption 2: Surgical alterations of the nasal skeleton produce purely regional changes. Bridge reduction affects the nasal width and nasal length, apparent nasal base size, middle vault support, alar rim contour, and columellar position. Similarly, alar cartilage reduction can affect tip support and projection, nasal length, alar rim contour, and external valvular support. Structural interdependencies in the nose are “global” not regional, and by understanding these interrelationships the surgeon may control the postoperative result.

Mark B. Constantian, MD
Rhinoplasty of the New Millennium
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