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Measurement of Radiometric Surface Temperature and Integrated Backscattered Light Intensity During Feedback-Controlled Laser-Assisted Cartilage Reshaping

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Abstract. Cartilage undergoes characteristic mechanical stress relaxation following laser irradiation below the ablation threshold. Porcine auricular cartilage (1–2 mm thickness) was irradiated with a Nd:YAG laser (λ=1.32 μm) at two power levels (W/cm^2). Surface temperature ($S_c(t)$ (°C)) (monitored using a single element HgCdTe infrared detector, 10–14 μm spectral range), and integrated back scattered light intensity $I(t)$ were measured during laser irradiation. A HeNe laser beam (λ=632.8 nm) was incident on the back surface of the cartilage specimen and fractional integrated backscattered light intensity was measured using an integrating sphere and a silicon photodiode. Laser irradiation (5.83 W/cm^2, 50 Hz pulse repetition rate (PRR)) continued until surface temperature reached approximately 70°C, during which cartilage mechanical stress relaxation was observed. Integrated back scattered light intensity reached a plateau at about 70°C). At higher laser power (39.45 W/cm^2, 50 Hz PRR), a feedback-controlled cryogen spray was used to maintain surface temperature below 50°C. A similar plateau response was noted in integrated backscattered light intensity. This signal may be used to optimise the process of stress relaxation in laser cartilage reshaping. Several clinical applications involving reconstructive surgery are proposed.

Keywords: Cartilage; Laser-induced reshaping; Nd:YAG laser; Plastic surgery; Reconstructive surgery; Stress relaxation

INTRODUCTION

Cartilage is a complex macromolecular tissue composed of 80% water, 13% collagen (Type II), and 7% protein–polysaccharide (proteoglycans). The collagen and proteoglycan molecules are synthesised by the chondrocyte, the constitutive cell of cartilage tissue. Collagen Type II forms a rigid framework that encases large meshes of proteoglycan macromolecules (100–200 MDa) containing copious numbers of charged species, chiefly COO^- and SO_3^- moieties at physiologic pH. In the collagen mesh, proteoglycans are compressed approximately 20 times their native size in free solution. As a consequence, electrostatic repulsion exists between negatively charged ion species that is only partially balanced by free counter ions in solution. This electrical imbalance results in an intrinsic tissue turgor termed the Donnan osmotic pressure [1–3]. The extrinsic morphology of cartilage is determined by the interplay of these ionic forces, ion and fluid flow in the matrix, and the tensile properties of the collagen mesh [2,3].

Cartilage forms the framework for several key aesthetic and functional structures in the head, neck and thorax, and can be used as autologous graft material in surgical reconstruction of auricular and nasal deformities, as well as tracheal and laryngeal defects. Surgery involving these structures is performed secondary to trauma, congenital malformation or chronic illness. At present,

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autologous cartilage is harvested from the pinna of the ear, costal margin (rib) or nasal septum and used at heterotopic sites. In auricular, nasal or tracheal reconstruction, the cartilage must be reshaped into complex shapes to conform to the anatomical defect by carving or suturing with steel or plastic sutures. However, such procedures require the harvesting of excessive donor tissue and severely limit the extent of potential reconstruction. This is particularly true with laryngotracheal reconstruction in the neonate and paediatric populations where insufficient cartilage is available for harvest.

Surgical alteration of native cartilage has been attempted using a wide range of methods. In the 1960s, Fry introduced the concept of 'interlocked stresses' [4,5]. When a flat sheet of cartilage was scored on one side and then allowed to soak briefly in saline solution, the tissue would curve with the concavity being on the side opposing the partial thickness incisions. Subsequent work by Fry et al. who studied shape changes in cartilage in response to thermal denaturation, demonstrated that this phenomenon was dependent on both the proteoglycans and collagen in the tissue [6].

The plastic deformation of cartilage via laser-mediated stress-relaxation was introduced by Sobol, using radiation emitted at $\lambda=10.6$ μm (CO_2) or $\lambda=2.12$ μm (holmium:YAG), in ex vivo animal and human cartilage [7–13]. Native cartilage can be reshaped into stable new geometries using laser irradiation without carbonisation or ablation. Sobol has suggested that the stress-relaxation in cartilage induced by moderate heating is due to the redistribution of water and free ions within the complex cartilage matrix or change in proteoglycan structure. Laser irradiation can be used to heat cartilage in a precise manner that is primarily dependent on the wavelength, pulse duration, irradiance, and tissue absorption and scattering coefficients. Cartilage undergoes a characteristic phase transformation at about 70°C [12]. For thin specimens, reshaping can be induced using a CO_2 laser at an irradiance of 50–70 W/cm^2 with a total energy dose of 1200–1800 J/g [12]. For thick specimens and relatively long irradiation periods, the holmium:YAG laser was found to produce a relatively uniform temperature distribution in a 1 mm thick specimen at a fluence of 1.9 J/cm^2. Wang et al. [14,15] performed studies in vivo on a crushed canine trachea through an endoscopic approach using a pulsed Nd:YAG laser ($\lambda=1.44$ μm). Cartilage and its overlying mucosa were simultaneously irradiated at a power density of 7 W/cm^2. Irradiation was stopped after a variable time period (5–6 min) determined by the subjective decrease in tensile strength needed to hold the warped cartilage in a desired position and shape.

Dynamic cooling via cryogen spray has been used to minimise non-specific thermal damage in skin while maximising destruction of targeted subsurface structures during pulsed laser treatment of port-wine stains [16]. Rapid (within 10–40 ms) surface temperature reduction by 30–40°C is obtained in response to a cryogen spurt (of milliseconds duration) as a consequence of liquid–vapour phase transition in the spray [17]. A variation of this approach has been used for spatially selective photocoagulation in tissue with an infrared radiometry feedback system during continuous laser irradiation [18]. Cryogen application can result in preservation of superficial tissues with coagulative necrosis of the underlying tissue.

In this study, laser-assisted cartilage shaping was accomplished using a Nd:YAG laser while radiometric surface temperature ($S_c(t)$ (°C)) and integrated backscattered light intensity $I(t)$ were measured simultaneously. It was our objective to determine the role of $S_c(t)$ and $I(t)$ measurements in optimising laser cartilage reshaping. In addition, we examined the utility of feedback-controlled cryogen spray cooling to maintain surface temperature below 50°C during prolonged laser irradiation and minimise thermal injury due to uncontrolled heating [16–18].

MATERIALS AND METHODS

Specimen Preparation

Fresh porcine auricular cartilage was obtained from a local abattoir (Clougherty Packing Company, Vernon, CA) within two hours after euthanasia. The pinna of the ear was removed with a scalpel and the soft tissue including the perichondrium dissected free from the cartilage using a Freer elevator leaving only the cartilaginous framework. The specimens were cut into rectangular shapes, of thickness Δ_c which was measured with a digital micrometer, and stored in physiological saline. They were used within four hours.

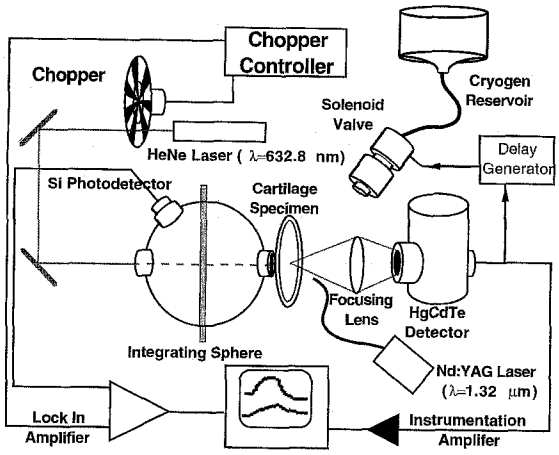

Fig. 1. Schematic for light scattering, radiometric surface temperature measurements, and feedback-controlled cryogen spray cooling. The cartilage specimen is secured on a mounting aperture at the focal point of the IR optical system. The HgCdTe IR detector, Nd:YAG laser, and cryogen cooling apparatus are directed toward the target site. The measured temperature $S_c(t)$ is used as a feedback signal to control the cryogen cooling. A chopped HeNe laser beam is directed on the back surface of the cartilage specimen through an integrating sphere. A silicon photodetector measures the backscattered light signal $I(t)$.

The cartilage specimens were first wrapped around a wooden dowel and secured at the edges with steel sewing pins. Then, the convex surface of the cartilage was irradiated by the laser. Only $S_c(t)$ was recorded during cartilage shaping experiments. When radiometric surface temperature reached 70°C the laser irradiation was stopped. In contrast to previous studies [9,11–13], laser irradiation was performed along the entire curved/stressed portion of the cartilage by rotating the specimen-dowel complex approximately 30° after each laser exposure. For light-scattering studies a separate experimental set-up was employed (Fig. 1) and no attempt was made to reshape the specimen. The flat specimens were suspended across the aperture bracket of the infrared (IR) radiometry apparatus while $I(t)$ and $S_c(t)$ were recorded during laser irradiation.

Laser Parameters

Cartilage specimens were irradiated with a Nd:YAG laser (λ=1.32 μm, 50 Hz pulse repetition rate (PRR), NewStar Lasers, Auburn, CA) delivered by a 600 μm core-diameter silica multimode optical fibre. Spot size was estimated using thermal paper. Laser power was measured with a pyroelectric meter (Model 10A-P, Ophir, Jerusalem, Israel). The reshaping and light-scattering studies were performed at low power (2 W, 5.83 W/cm^2), whereas higher power (10 W, 39.45 W/cm^2) was used for feedback-controlled cryogen spray cooling investigations.

Radiometric Measurements

Radiometric surface temperature ($S_c(t)$ (°C)) was monitored using a 1 mm^2 liquid N_2-cooled HgCdTe detector (MDD-10E0-S1, Cincinnati Electronics, Mason, OH) as previously described [17] (Fig. 1). The detector element was at the object plane of a 25 mm diameter f/1 Ge lens, optically filtered by a 10–14 μm bandpass filter (RL-7500-F, Corion Co, Franklin, MA). The collection optics were configured for unit magnification with a 5 mm diameter exit pupil positioned 50 mm from the detector resulting in a f/10 system. The detector probe area (when focused) was approximately 1mm in diameter. Temperature of the detection system was calibrated with an aluminium block coated with highly emissive (ε=0.97) black paint (TC-303 black, GIE Corp, Provo, UT) heated from 23 to 100°C by a resistive element. Surface temperature of the aluminium was measured with a precision thermistor (8681, Keithley Instruments, Cleveland, OH) attached to the block. For cooling studies, the radiometric signal at the centre of the laser target site served as a feedback signal to trigger the delivery of sequential cryogen spurts (duration 40 ms) when the surface temperature reached a predetermined value (50°C).

Cryogen Spray Cooling

The test cryogen (Chlorodifluoromethane, boiling point −40°C, Aldrich Chemical Company, Milwaukee, WI) was stored in a pressurised (~5 atm) reservoir, and delivered by an electronically controlled solenoid valve (aperture diameter 1 mm) creating a 7 mm diameter cooled region on the surface of the cartilage. Distance between the solenoid valve orifice and the cartilage surface was maintained at 20 mm. The cryogen spurt duration (40 ms) was controlled by a programmable digital delay generator (DG 535, Stanford Research Systems, Sunnyvale, CA).

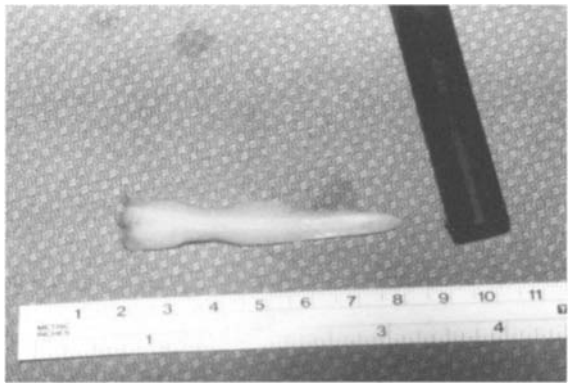

Fig. 2. Native cartilage specimen before laser irradiation. The cartilage is flat and without curvature. The specimen is subsequently wrapped around a wooden dowel during laser irradiation.

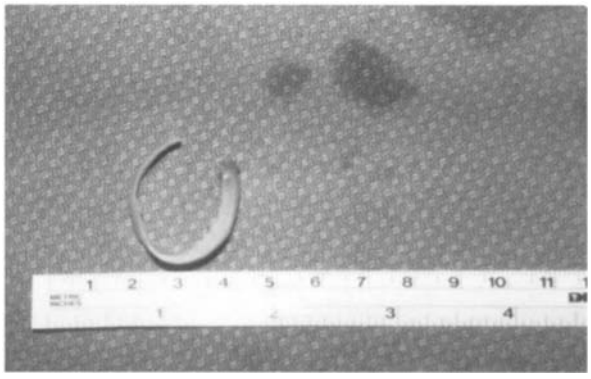

Fig. 3. Laser-shaped cartilage specimen following Nd:YAG laser irradiation while wrapped around wooden dowel. Cryogen cooling was not used.

Light-Scattering Measurements

Backscattered light $I(t)$ from the HeNe laser (λ_0=632.8 nm, 15 mW, Melles Griot, Carlsbad, CA) incident on the non-irradiated surface of the cartilage specimen was collected in an integrating sphere (6 in. diameter, IS-060, Labsphere, North Sutton, NH) and measured using a silicon photodetector (Model 2001, New Focus, Mountain View, CA). In order to improve the signal to noise ratio, HeNe laser intensity was amplitude modulated (1000 Hz) with a mechanical chopper (Model R540, Stanford Research Systems, Sunnyvale, CA) and synchronously detected by a lock-in amplifier (Model SR 850, Stanford Research Systems, Sunnyvale, CA). During laser irradiation, the fractional change in integrated backscattered light intensity ($\Delta I(t)/I_0$) was calculated by recording the change in $I(t)$ relative to the baseline integrated backscattered light intensity signal I_0 (which is measured prior to Nd:YAG laser irradiation). Both the scattered light and radiometric temperature signals were displayed on a digital storage oscilloscope (Textronix DSA 601, Beaverton, OR).

RESULTS

The flat cartilage in Fig. 2 was irradiated with the Nd:YAG laser which resulted in marked surface curvature (Fig. 3) demonstrating the possibility of creating curved tracheal segments from a native specimen. These changes were produced by irradiating the cartilage specimens while they were wrapped around the wooden dowel. Individual regions of the cartilage were irradiated approximately every 30° of axial rotation. Figure 4(a–d) depicts a series of plots corresponding to experiments where laser irradiance was 2 W (5.83 W/cm^2). The cartilage specimens were held flat against the integrating sphere as depicted in Fig. 1; no curvature (e.g. wooden dowel) was imposed on the specimen. Each figure represents a different cartilage specimen with thickness Δ_c varying between 1–2 mm. Feedback-controlled cooling was not employed and laser radiation was terminated when $S_c(t)$ reached approximately 70°C. The precise shape of $\Delta I(t)/I_0$ during heating appeared to be highly sensitive to cartilage position and varied between specimens. However, the plateau region of the fractional change in intensity ($\Delta I(t)/I_0$) occurred during the same temperature interval (65–70°C) for all specimens.

In Fig. 5, a cartilage specimen was irradiated for 4 s at high power (10 W, 39.45 W/cm^2, 50 Hz PRR), and feedback-controlled cryogen spray was used to cool the laser target site and prevent $S_c(t)$ from rising above 50°C. Three cryogen spurts were delivered during continuous laser irradiation at each point when $S_c(t)$ reached 50°C. Despite rapid fluctuations in $S_c(t)$, $\Delta I(t)/I_0$ continued to increase and did not plateau until laser irradiation terminated (as evidenced by the monotonic decline in $S_c(t)$.

DISCUSSION

Laser-assisted reshaping of native cartilage may provide a more effective means for morphological and structural reconstruction than conventional surgical techniques. Several key elements require further investigation before the technique may be applied clinically. The

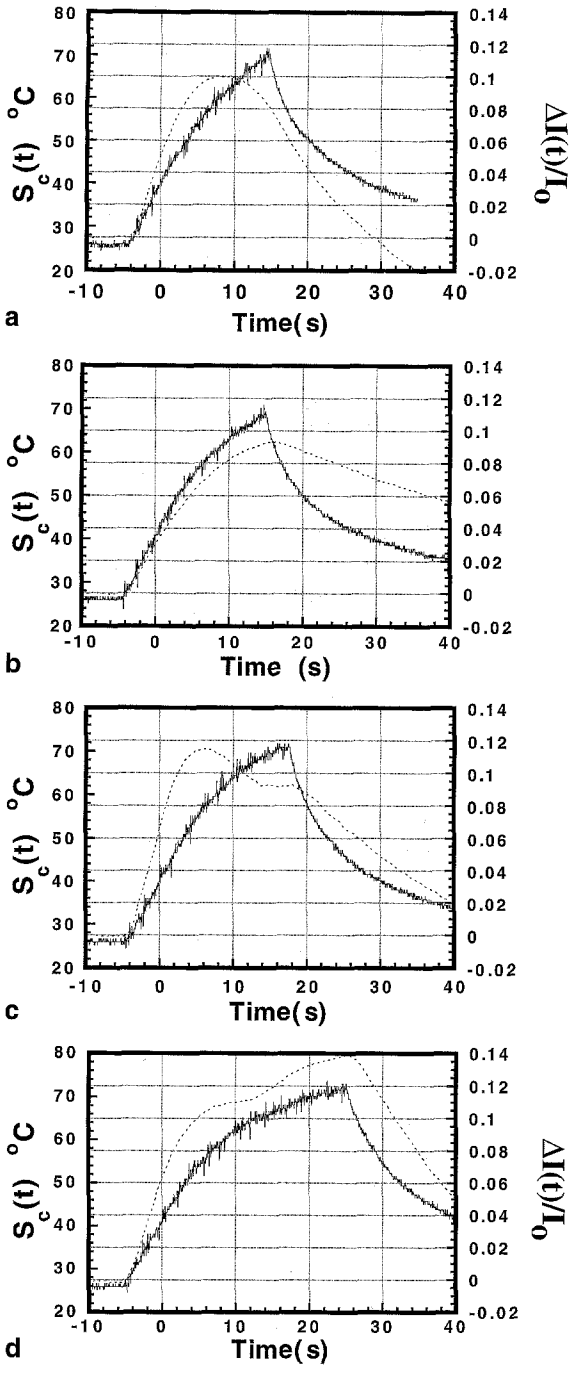

Fig. 4. Simultaneous measurements of radiometric surface temperature $S_c(t)$ and fractional change in integrated scattered light intensity $\Delta I(t)/I_0$. The shape of $\Delta I(t)/I_0$ is highly variable and sensitive to specimen thickness and geometry, however the stationary region where the slope is zero remains constant, and this consistently occurs during the temperature transition from 65 to 70°C. (a) The peak for $\Delta I(t)/I_0$ occurs prior to the 70°C threshold for tissue denaturation. (b) $\Delta I(t)/I_0$ assumes a biphasic shape yet retains the inflection change in the temperature interval between 65 and 70°C. (c) A biphasic shape for $I(t)/I_0$ is noted, though the peak occurs prior to the surface temperature reaching 70°C. (d) Temperature did not exceed 70°C in this specimen and the peak in $\Delta I(t)/I_0$ occurs after the temperature peak (at about 67°C). Laser radiation was stopped before $S_c(t)$ reached 70°C. —— $S_c(t)$, · · · $\Delta I(t)/I_0$.

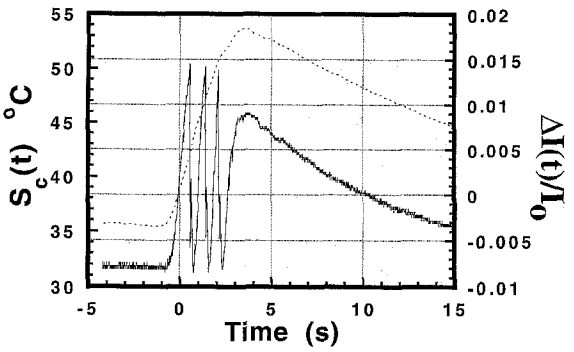

Fig. 5. Feedback-controlled laser-assisted cartilage reshaping with cryogen spray cooling. Three cryogen spurts were initiated when radiometric surface temperature exceeded 50°C. The duration of the cryogen spurts was 40 ms. The scattered light signal peaks during the cessation of laser irradiation. —— $S_c(t)$, · · · $\Delta I(t)/I_0$.

first and foremost concern is cartilage viability. To date, no 'dose–response' curves for cartilage viability following laser irradiation (below the ablation threshold) have been derived. Although limited histological studies have been completed [14], the cartilage viability in response to laser-mediated heating is under investigation in our laboratory. Second, optimal laser parameters to mediate stress relaxation in cartilage have not been identified. Undoubtedly, moderate heating (i.e. non-ablative energy densities) in combination with a feedback control system are necessary to minimise non-specific thermal injury.

Our preliminary measurements indicate that marked surface temperature elevations occur rapidly even with moderate power densities (Fig. 4a–d). The degree of thermal injury is dependent on the spatial and temporal distribution of temperature as well as the light distribution in the tissue [19]. As an estimate for tissue devitalisation, we used a surface temperature threshold of approximately 70°C (at which irreversible protein denaturation occurs). With cryogen cooling, surface temperature may be maintained below a predetermined temperature threshold. In Fig. 5, $\Delta I(t)/I_0$ reaches a peak with the cessation of laser irradiation when surface temperature is kept below 50°C. We speculate that with prolonged irradiation (>30 s) and cryogen cooling, $\Delta I(t)/I_0$ would plateau and then decrease despite continued laser irradiation. In future studies, we plan to measure $\Delta I(t)/I_0$ and $S_c(t)$ while simultaneously measuring intrinsic stress in the cartilage specimen during laser reshaping.

When feedback-controlled cryogen spray cooling is used, the surface temperature of the

cartilage specimen can be maintained below a specified level. Dynamic cooling has the advantage of providing precise temperature control in contrast to simple laser power modulation, as steep thermal gradients for cooling (and thermal relaxation) are established. When the cryogen contacts the target site, heat is liberated from the cartilage to the cryogen across a large thermal gradient. The cryogen evaporates and the target site is rapidly cooled [17]. As illustrated in Fig. 5, three cryogen spurts were required to maintain the surface temperature below 50°C during Nd:YAG laser irradiation. Although power densities used in this study did not create tissue coagulation or ablation, it is probable that subsurface temperature may exceed 70°C during sustained moderate laser irradiation; $S_c(t)$ may actually be cooler than the immediate subsurface temperature due to evaporative heat losses. During cryogen-cooled cartilage reshaping, radiometric surface temperature measurements may be inadequate alone to predict tissue injury (subsurface temperatures may exceed 100°C) and, therefore $I(t)$ may be a more sensitive means to determine the critical point when the shape–phase transformation occurs.

The fractional change in scattered light intensity $\Delta I(t)/I_0$ represents an estimate of the change in target site optical properties during laser irradiation and is dependent on the light distribution of the HeNe (λ=632.8 nm) probe beam (deeply penetrating in opaque tissues) and the Nd:YAG (λ=1.32 μm) laser causing the temperature change. Laser light at 1.32 μm is weakly attenuated by cartilage, and hence the light distribution is more uniform across thin cartilage specimens (Δ_c=500–1000 μm). The HeNe laser probe beam is more highly scattered and changes in $I(t)$ are due to backscattering interactions in the superficial tissue layers. With moderate heating (and no cooling) $I(t)$ reaches a plateau when $S_c(t)$ is between 65 and 70°C as seen in Fig. 4. Sobol et al. [12] also observed this plateau effect in transmitted laser light. Although additional experiments are necessary to interpret the molecular basis of the light-scattering results, the stationary region where the slope of $\Delta I(t)/I_0$ is zero may correspond to the water phase transition hypothesised by Sobol [10]. Initially, local regions or 'islands' of anomalous refractive index form when water bound to large proteoglycan molecules is liberated. In the theory of laser-induced phase transitions, these 'islands' are viewed as nucleation sites [10]. As the bound-to-free water phase transition nears completion, regions of anomalous refractive index become larger and eventually coalesce into a homogeneous phase. The resultant change in slope of $\Delta I(t)/I_0$ needs to be identified during sustained laser irradiation with cryogen cooling and such studies are presently underway in our laboratories.

CONCLUSIONS

In summary, results of these studies demonstrate that the process of laser-induced stress-relaxation in cartilage is accompanied, and may be monitored, by changes in the fractional change of integrated backscattered light intensity $\Delta I(t)/I_0$. Cryogen cooling may be a useful technique to allow rapid delivery of laser energy while simultaneously minimising potential non-specific thermal injury. Radiometric surface temperature $S_c(t)$ may be less sensitive to the stress relaxation process in cartilage reshaping, but the guidance provided by such measurement minimises the side effects of uncontrolled heating. Inasmuch as stress relaxation is always accompanied by changes in tissue optical properties, design of a feedback control system appears feasible. Nevertheless, since the correlation between observed changes in $\Delta I(t)/I_0$,$S_c(t)$, and optimal laser irradiation parameters is not known, further laboratory experiments are needed to provide more information on the mechanism of this thermo-optical mediated mechanical change. The clinical impact of laser-assisted cartilage reshaping would be most dramatic in airway and nasal reconstruction surgery. The same methodology also has the potential for wide use in arthroplasty and other orthopaedic surgical procedures, particularly for pathology due to trauma or rheumatological disease.

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