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Time and Frequency Resolved XeCl Laser-Induced Mechanical Transients in Otic Capsule Bone

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Abstract

Objective—This study identifies the presence of photoacoustic waves during excimer laser treatment of porcine otic capsule bone.

Background Data—Pulsed ultraviolet lasers have been suggested for use in middle ear surgery due to their potential for fiberoptic delivery, decreased thermal trauma, and precise ablation characteristics. However, the short pulse width of excimer lasers (typically 10–150 ns) can create large thermoelastic stresses in the ablation specimen.

Materials and Methods—A XeCl ($\lambda = 308$ nm, $\tau = 12$ ns) excimer laser was used to ablate wafers of bone with energies of 90, 35, 13, 5, and 1.8 mJ/pulse. Custom high-frequency polyvinylidene difluoride (PVDF) piezoelectric film transducers were fabricated and attached to the slices of bone. During ablation photoacoustic signals were amplified using a low-noise preamplifier and recorded on a digitizing oscilloscope.

Results—Photoacoustic waves were clearly identified. Stress wave amplitude increased with laser fluence.

Conclusion—A laser fluence must be found that compromises between an increased ablation rate and increased stress wave amplitude. The acoustic power levels generated during ablation are below maximum exposure limits.

INTRODUCTION

A number of different lasers are used clinically for middle ear surgery.¹ Excimer laser light provides precise ablation of bone with minimal thermal damage to the surrounding tissue.^{2,3} Segas et al.⁴ demonstrated the efficacy of using excimer lasers for changing the shape of the middle ear ossicles during ear surgery in an experimental model. Scanning electron

microscopy of ossicles showed minimal surface damage beyond the laser target site. Though there are concerns over injury from heat conduction to the inner ear with excimer laser irradiation, this was not demonstrated in an inner ear model irradiated by an excimer laser.⁵ The short pulse length of this laser satisfies the conditions for thermal confinement⁶ and minimizes tissue trauma due to heat conduction. These precise ablation characteristics make excimer lasers attractive devices for middle ear and ossicular surgery.^{7,8} Despite these advantages, excimer lasers may create photoacoustic injury through the generation of mechanical transients.⁹ These high-amplitude and high-frequency mechanical transients may create tissue damage, for example tears in the tissue beyond the ablation crater edge. The formation of cracks or fractures may occur in regions of stress concentration as high pressures develop in the ablation cavity.^{10,11} High-intensity shockwaves are also capable of destroying osteocytes and blood cells.¹² High-intensity short-lived acoustic signals may also result in noise-induced hearing loss.¹³

In this study, we measured photoacoustic transients created by XeCl laser ablation of porcine otic capsule,¹⁴ and examined their frequency characteristics to determine its suitability for inner ear surgery. The time-resolved results are compared to an analytic model derived from a solution to the thermal-elastic stress equation.¹⁵

MATERIALS AND METHODS

Otic capsule bone tissue was removed from the temporal bone of a freshly sacrificed pig skull obtained from a large regional packing company (Clougherty Packing Company, Vernon, CA) as previously described.^{14,16} The animal was of slaughter age, approximately 21 wk old. The bone surrounding the structures of the inner ear is called endochondral bone and forms the otic capsule. It is a primitive form of bone with dense extracellular matrix components. The otic capsule surrounds the membranous labyrinth and provides a hard bony casing to protect the organs of hearing and balance. At 21 wk of age the otic capsule is fully ossified. Fresh otic capsule bone was stored in saline at 4°C and used within 24 h. A low-speed microstructural saw with a diamond wafering blade (Model 11-1180 Isomet; Buehler Ltd., Lake Bluff, IL, USA) was used to machine the bone into individual slices of uniform thickness varying from 0.5 to 2.0 mm. The cut surface of this bone is smooth and homogeneous.¹⁷ Each individual slice was inspected for uniformity in thickness using a micrometer and evaluated visually with a low-power microscope to ensure gross uniformity. Specimens with marked heterogeneity were discarded. Thin sections of bone were used because artifact may be introduced by using intact porcine otic capsule which has fluid-filled spaces of the membranous labyrinth. Each specimen was weighed on an analytic balance to determine its mass. The thickness of each slice was measured with a digital micrometer. The surface area of the bone specimen was determined by making an 800% photocopy enlargement of the specimen on graph paper.

A XeCl laser ($\lambda = 308$ nm, $\tau = 12$ ns) (FWHM) (Lumonics HyperEX-400; Kanata, Ottawa, Ontario, Canada) was used to ablate the tissue. Fig. 1 shows the schematic of the experimental setup. The radiation was focused onto the target site with a quartz lens ($f = 10$ cm). Laser pulse fluence was varied by attenuating the beam with silica glass slides. Energy per pulse from the laser was measured using a joulemeter (Model ED-500; Gentec Electro-

Optics Inc., Quebec, QC, Canada), and varied among 90, 35, 13, 5, and 1.8 mJ/pulse. Spot size was determined by a single pulse measurement on burn paper. At 35 mJ/pulse the beam area was estimated to be 1 mm². Energy density per pulse was 0.9, 0.35, 0.13, 0.05, and 0.018 J/cm². The beam was focused onto the otic capsule bone specimen, which in turn lay on top of a piezoelectric transducer.

The piezoelectric transducer was constructed from polyvinylidene fluoride (PVDF) film (28 μ m thickness) sputter coated with NiCu (AMP Corporation, Valley Forge, PA, USA). A 5.5 $\times$ 16 mm rectangular piece of PVDF was bonded to a large acrylic glass block (80 $\times$ 60 $\times$ 40 mm) with low-viscosity methylmethacrylate glue. A small 3.5-mm strip of PVDF overhung the edge of the acrylic block. Electrodes made from conductive copper foil tape (3M part no. 1181; 3M, St. Paul, MN, USA) were fastened to this strip and secured in place with quick-drying epoxy cement. Ultrasonic jelly (Echotrack; Echo Ultrasound Co., Reedsville, PA, USA) was placed between the PVDF and the bone specimen in order to minimize acoustic reflections. The entire acrylic block and transducer were mounted on a X-Y-Z positioner. An aperture (2 mm in diameter) was placed 2 mm above the target surface to minimize the detection of light scattered from the laser on the portions of the PVDF transducer not covered by bone. A silicon photodiode ($\tau < 1$ ns) (FND-100 Judson; Technologies LLC., Montgomeryville, PA) measuring the scattered laser light was used to generate a trigger signal.

The bone slice was irradiated with each of the laser energies. Irradiation of one specimen ensured comparison of data from areas of comparable mass and geometry. The signals from the PVDF transducer and the silicon photodiode were displayed on a digital oscilloscope (Tektronix DSA 601; Tektronix, Beaverton, OR, USA). The waveforms were stored digitally and transferred to a Macintosh laboratory computer system for further analysis.

RESULTS

Fig. 2 is an illustration of the temporal behavior of the mechanical transient measured from an otic capsule bone slice (thickness 0.77 mm, surface area 21.68 mm², mass 0.0335 g) irradiated with a single 35-mJ pulse. The ordinate is expressed in kilopascals, which was determined from the voltage output of the transducer, the piezo stress constant ($g_{33} = -339 \times 10^{-3}$ V m N⁻¹ for PVDF¹⁸), and the thickness of the PVDF transducer (28 μ m). The first peak in the waveform represents the compression and rarefaction wave generated by the laser pulse as it traverses the specimen from the ablation site to the PVDF–bone interface. The second peak represents an echo that results from the reflection of the original wave at the bone–air interface. The speed of sound in otic capsule was calculated from the specimen thickness and the time interval between the original pulse and the echo. It was estimated to be 4350 ± 140 m/s⁻¹ based on 70 individual measurements. Later echoes are also seen but with reduced amplitude. The small shift in the baseline following the first rarefaction wave may result from the conversion of some acoustic energy into heat in the PVDF transducer, which also has a large pyroelectric constant (-30×10^{-6} C m⁻² K).

A power spectrum obtained from a fast Fourier transform of the first transient waveform in Fig. 2 is illustrated in Fig. 3. Note the center frequency of this transient is 6 MHz.

Fig. 4 illustrates the stress-rarefaction wave in a 1.36-mm-thick slice of otic capsule bone (mass = 0.0575 g, surface area = 20 mm²) treated at five different fluences. This specimen was ablated with one pulse at each of the following fluences: 90, 35, 13, 5, and 1.8 mJ. The stress component increases with increasing fluence. In contrast, the amplitude of the rarefaction component increases initially, and then disappears at high fluences, where plasma formation and audible popping were observed. The broadening of the stress wave for high fluences may reflect not only the larger mechanical transient in the bone, but also the momentum transferred to the specimen from the violent release of ablation products with the plasma.

Fig. 5 depicts the amplitudes of the stress and rarefaction waves as a function of fluence.

At high fluences (90 and 35 mJ) loud popping noises were audible and plasma formation was observed. The popping sounds heard at 35 mJ were not as loud as those heard at 90 mJ. An ablation crater was noted at 90 mJ fluence. At low fluences (13, 5, and 1.8 mJ) no discernible popping sound or evidence of plasma formation was observed.

DISCUSSION

Silica glass slides were used to attenuate the XeCl laser beam in order to preserve the beam profile. As a consequence it was not possible to generate fluences between 35 and 90 mJ/pulse. Despite this limitation, a parabolic rarefaction wave was observed (Fig. 5). The positive values for rarefaction waves seen at high fluence reflect the recoil momentum created by the violent release of ablation products. This is in good agreement with Esenaliev et al.,¹⁹ who used a model with CuCl₂ solution and atherosclerotic blood vessels.

It was necessary to irradiate a single specimen with each pulse energy because the mass and geometry varies between individual specimens. Although irradiation may alter the tissue structure, the effect is assumed to be negligible. Ablation is only apparent with the highest energy level, so the pulses were applied in order of increasing energy. In this way changes to the sample are minimized until the last pulse.

PVDF piezofolios are widely used in the study of photo-acoustic transients in both hard and soft tissues. Optimally, the transducer element is very small and the laser beam very wide in order to approximate a plane wave configuration. This is not possible using otic capsule tissue. It is irregularly shaped with large cavities for the cochlea and acoustic nerve and measures approximately 1 × 1 × 2 cm.²⁰ It also has several small holes within it to accommodate the semicircular canals of the vestibular system and the various nerves that traverse the skull base. It is not possible to obtain a sample of sufficient size such that the surface area of the specimen is much larger than the area of the smallest transducer we could fashion (3 × 3 mm), and thus provide a planar wave approximation.

The voltage signal from the PVDF detector is proportional to the total mechanical energy in the flat bone specimen generated by the laser pulse. The excess piezofoil surface area that is not in direct contact with the bone effectively acts as excess capacitance, and low-pass filters the signal.²¹ PVDF will also absorb scattered UV laser radiation. In the absence of an aperture placed above the target site, scattered laser light produces a huge photoelectric

signal (an order of magnitude larger than the mechanically-induced signal we measured). The aperture effectively removed this stray energy and should be considered when using PVDF with wavelengths it heavily absorbs.

As can be seen in Fig. 2, there is a slight baseline shift between the initial bipolar thermoelastic wave and its echoes. This may be due to residual scattered light not eliminated by the aperture, and/or heat from the conversion of acoustic energy generating a pyroelectric signal. This signal is not due to heat transfer from the ablation site across the thickness of the specimen. Given the thickness of the specimen and the diffusivity of bone (assumed to be within an order of magnitude of the diffusivity of water), the signal from thermal diffusion would be expected after a time delay on the order of 1 s.

Thermal-elastic stress-rarefaction waves have been modeled in several soft tissues at fluences above and below the threshold for ablation using different short-pulse lasers.^{22–24} An exponential solution to the one-dimensional thermal-elastic wave equation was derived,¹⁵ and the solution is dependent on the rise and fall time constants of the laser, acoustic impedance of the target, absorption coefficient, and Grüneisen coefficient. The precise measurement of a thermal-elastic wave created by laser irradiation below the threshold for ablation permits the estimation of all these parameters.¹⁹ Above the threshold for ablation, these equations are no longer valid, as the recoil stress momentum imparted to the target site by ablation products cancels out the rarefaction wave. This contributes to the overall broadening of the stress wave component.

At low fluence, the magnitude of the stress component is nearly identical to that of the rarefaction wave as seen in Fig. 4. The generation of the rarefaction wave occurs due to the large impedance mismatch between the bone and air, and its peak magnitude can be calculated knowing the acoustic impedance of both media.¹⁹ In a constrained surface (such as water), the bipolar shape is neither observed nor predicted from theory.²² The magnitude of the stress component increases with fluence, but this is not accompanied by a matching increase in the magnitude of the rarefaction wave (Fig. 4). When ablation occurs, particles are expelled from the target site at high velocities over a short time interval, which leads to the creation of intense stress waves.²⁵ The waves generated by imparted recoil momentum cancel out the rarefaction wave. This is graphically illustrated in Fig. 5, where the peak amplitudes of the stress and rarefaction waves are plotted as a function of fluence.

Fig. 3 illustrates the spectral characteristics of a thermal-elastic wave. The peak amplitude occurs near 6 MHz. Useful hearing is between 250 and 4000 Hz, though the human ear is sensitive up to 20,000 Hz.

At 90 mJ a stress wave of amplitude 152 kPa was generated. Compared to the reference sound power in air, this corresponds to 127 dB. The National Institute for Occupational Safety and Health (NIOSH) recommends that exposure to this power level should be limited to less than 1.8 s.²⁶ Since the waves generated in this study are of the order of microseconds, this would suggest that the noise produced does not exceed safe limits. However, occupational noise exposure tables and acoustical trauma data do not include ultrasonic frequencies. The effects of a high-amplitude ultrasonic wave traversing the otic capsule

(with the cochlea within) have not been studied. The acoustic wave is attenuated by conversion to heat and scattering due to inhomogeneous media. Attenuation of the acoustic wave proceeds exponentially as a function of the damping coefficient.¹⁹ In turn the damping coefficient increases proportionally with the square of the frequency, though this dependence is highly variable in tissue. Significant attenuation of an acoustic wave at 10 MHz occurs in about 1 cm in tissue.¹⁹ Although pulsed lasers have been used in several models of ear surgery,^{27–32} there has not been a study of the audiologic sequelae.

CONCLUSION

This study demonstrated the presence of thermal-elastic and ablative stress transients in XeCl laser-ablated otic capsule bone. PVDF piezofilms were used to measure the laser-induced mechanical transients in this bone tissue and examine waveform characteristics above and significantly below the threshold for visible and audible ablation. The frequency resolved characteristics of the generated thermal-elastic waves were determined.

Ablation rate increases with laser fluence.¹⁶ However, so does the magnitude of the stress wave. Therefore a compromise must be made between achieving a good drilling rate and minimizing potentially damaging mechanical transients. The acoustic power levels generated during ablation of bone by a XeCl laser are below the NIOSH limit for permissible exposure. However, more research is required on the effect of the high-frequency stress waves produced here.

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FIG. 1.

Schematic representation of experimental setup used to measure photoacoustic waves. A 308-nm excimer laser was focused onto a thin section of otic capsule specimen securely mounted on a micro-adjustable stage. Photoacoustic signals were detected by a PVDF transducer. The signal was routed directly to a digitizing oscilloscope and signal analyzer. The trigger for the oscilloscope is provided by a fast silicon photodiode.

FIG. 2.

Photoacoustic waveform in porcine otic capsule measured using PVDF transducers. Characteristic stress-rarefaction waves are identifiable along with multiple acoustic reflections at the interface of the bone and the transducer.

FIG. 3.
Fast Fourier transform of transient wave from Fig. 2.

FIG. 4. Stress-rarefaction waves in a 1.36-mm-thick slice of otic capsule bone irradiated with 90-, 35-, 13-, 5-, and 1.8-mJ pulses.

FIG. 5.
Amplitudes of the stress and rarefaction waves as a function of fluence