Time-Resolved Studies of Nd:YAG Laser-Induced Breakdown

Plasma Formation, Acoustic Wave Generation, and Cavitation

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The use of high intensity ultrashort pulsed laser radiation to produce optical breakdown is an important approach for the surgical treatment of intraocular structures. We have investigated the transient properties of Nd:YAG laser induced breakdown in a saline model using time-resolved spectroscopic techniques. Spatially resolved pump and probe techniques are applied to study the dynamic behavior of the plasma formation, acoustic wave generation, and cavitation processes which accompany the optical breakdown. Measurements of plasma shielding and luminescence indicate that the laser induced plasma forms on a subnanosecond time scale and has a lifetime of several nanoseconds. An acoustic transient is generated at the breakdown site and propagates spherically outward with an initial hypersonic velocity, then loses energy and propagates at sound velocity. Transient heating following the plasma formation produces a liquid-gas phase change and gives rise to cavitation or gas bubble formation. This gas bubble expands rapidly for several microseconds, then slows to reach its maximum size and finally collapses. Invest Ophthalmol Vis Sci 26:1771-1777, 1985

Short pulsed Q-switched and modelocked Nd:YAG lasers have recently achieved widespread use in ophthalmic surgery. The ability of high intensity short laser pulses to induce optical breakdown and produce lesions from acoustic transient and cavitation effects has been especially important for the surgical treatment of intraocular structures in the anterior eye which are nominally transparent to the laser wavelength. The transient physical phenomena which accompany the optical breakdown process include laser-induced plasma formation, acoustic wave generation and propagation, as well as cavitation or gas bubble formation. These processes are relevant to the clinical effectiveness of optical breakdown and have direct implications on its physiological and pathological effects in the eye. The increased absorption of the laser-induced plasma has been shown to play a potentially important role in protecting the retina from the incident laser energy, while the clinically useful effects are primarily produced by the acoustic wave and cavitation.

In this paper we describe the experimental investigation of the transient phenomena associated with laser-induced optical breakdown through the application of time-resolved spectroscopic techniques. In particular we emphasize pump-probe measurements as a method for characterizing the transient temporal and spatial evolution of the breakdown process. The pump-probe technique relies on the use of two laser beams: one beam, the pump, is used to produce a change in the sample, while the other beam, the probe, measures the effects produced by the pump. In this investigation a Q-switched Nd:YAG is used as the pump laser to induce optical breakdown in a saline sample while a continuous wave HeNe laser is used to measure the transient changes in optical properties. The measurement of both spatial and temporal behavior allows the characterization of plasma formation, acoustic wave generation, and cavitation which accompany the breakdown as well as a determination of the physical dimensions and propagation velocities associated with these phenomena. While previous researchers have examined laser-induced breakdown using a variety of techniques including high speed photography and holography, transient luminescence and pulse transmission detection, and acoustic transducer measurements, the spatially resolved pump-
probe technique is one of the few approaches which permits the investigation of a wide variety of physical processes in a simple and consistent experimental framework.

**Materials and Methods**

The experimental configuration for pump-probe measurements of laser-induced optical breakdown is shown schematically (Fig. 1). For our investigations, optical breakdown was studied in a simple model system consisting of physiological (0.9%) saline solution. The saline was contained in a $10 \times 20$-mm quartz fluorimeter cell. In order to prevent the accumulation of gas bubbles or other impurities produced by the optical breakdown process, the solution was circulated and filtered with a 3-nm filter.

A frequency doubled Q-switched Nd:YAG laser (Quanta-Ray DCR1; Mountain View, CA) was used as the pump laser to produce optical breakdown in the sample. The Nd:YAG laser generates $\sim 10$ ns long pulses at 532 nm with a repetition rate of 10 Hz. The second harmonic of the Nd:YAG laser was used in order to facilitate accurate measurements of beam spatial profile and focusing characteristics. The laser was adjusted to optimize temporal pulse shape and energy stability. The pulse energy delivered to the sample was varied using beamsplitters and calibrated neutral density filters. Pulse energy measurements were performed with a Scientech Model 361 (Boulder, CO) pyroelectric energy meter. The laser output beam was 10 mm in diameter and focused into the sample cell with a 25-mm focal length lens. Since the Nd:YAG laser employed a diffraction coupled resonator, the spatial mode profile of the output beam was a "doughnut" rather than a Gaussian mode, and diffraction limit focusing was not expected.

The transient properties of the laser-induced breakdown were probed by a low intensity, 1 mW, continuous wave helium-neon (HeNe) laser ($\lambda = 632.8$ nm). In order to obtain a spatial resolution of better than 10 $\mu$m, the probe beam was first expanded to a diameter of 6 mm before being focussed into the sample cell with a 32-mm focal length lens. The focal point of the HeNe probe laser was carefully adjusted to coincide with the center of the breakdown region with the probe beam orthogonal to the pump beam. Since the breakdown region extends along the axis of the pump beam with increasing pump pulse energy, the probe alignment was adjusted after changes in the pump energy.

Spatially resolved pump-probe measurements of the breakdown process were obtained by varying the relative separation of the probe laser beam focus from the center of the breakdown region. This was accomplished by translating the pump beam steering and focusing optics in a direction orthogonal to the plane of Figure 1 using a 1-$\mu$m resolution stepping motor mechanical stage (Klinger Scientific; Richmond Hill, NY). The center of the breakdown region was determined by noting that the probe beam behavior should be symmetric for positive and negative displacements. The use of this spatially resolved technique facilitates the measurement of physical dimensions as well as the dynamic behavior of processes involving transient propagation away from the center of the breakdown region.

The transmitted HeNe probe beam was focussed onto a small area, high speed, avalanche photodiode detector (Telefunken BPW28; Sommerville, NJ). A narrowband dielectric interference filter centered at 632.8 nm was used to block luminescence and scattered light from the optical breakdown. The small area of the detector combined with this detection geometry makes the probe laser sensitive not only to changes in transmission arising from induced absorption or scattering, but also to changes in the index of refraction which will influence the imaging of the probe beam onto the detector. The temporal behavior of the laser-induced plasma luminescence was also measured by turning off the probe laser and using a low pass, red filter in front of the detector to block the scattered pump laser.
The output of the photodiode was measured with a high speed oscilloscope (Tektronix 7104; Beaverton, OR) with a 1 GHz bandwidth. Measurements which did not require high temporal resolution were performed using a high speed storage oscilloscope (Tektronix 7834). The temporal resolution was ~4 ns as limited by the duration of the Nd:YAG laser pulses. Experimentally, the effective temporal measurement resolution was limited by fluctuations in the laser-induced breakdown processes which occurred on a shot to shot basis rather than bandwidth restrictions in the electronic instrumentation.

Results

A sharp threshold for the onset of optical breakdown is observed with increasing Nd:YAG pump laser intensity. For our experimental conditions, using purified saline solution, threshold was ~6 mJ per pulse. The breakdown threshold was dependent on the purity of the saline sample and was reduced in the presence of impurities or gas bubbles in the solution. The breakdown process was evidenced by a dramatic increase in the scattering of the incident Nd:YAG laser and an audible noise from acoustic wave generation. Plasma luminescence and gas bubble formation were also visually observable.

Figure 2 shows the experimentally measured time-resolved plasma luminescence as well as pump probe measurements of induced absorption and scattering following the initiation of optical breakdown. Data was obtained for an incident Nd:YAG pulse energy of 20 mJ per pulse. Figure 2a shows an oscilloscope trace of the incident Nd:YAG laser pulse shape. The pulse duration is approximately 10 ns with a 4-ns temporal substructure. Figure 2b shows the temporal behavior of the plasma luminescence. The time scale for Figures 2a and 2b are identical, indicating that the plasma luminescence develops rapidly within ~4 ns after the incident pump pulse intensity reaches a level sufficient for its generation. The plasma luminescence does not have an identical temporal structure to the incident pump pulse, but rather exhibits a smoothed profile which resembles the envelope of the pump pulse with a ~10 ns exponential decay. If the plasma luminescence behavior is an indicator of the presence of the plasma, then these results indicate that the plasma lifetime is of the order of 10 ns. Figure 2c shows the temporal behavior of the transmitted HeNe probe laser on a time scale identical to the previous photographs. The HeNe probe beam focal point was made coincident with the central portion of the breakdown region. The decrease in the probe transmission begins within ~4 ns after the peak of the pump pulse and plasma luminescence. Transmission is reduced by >50% in less than ~3 ns. The risetime of the plasma luminescence as well as the onset of the induced absorption is limited in this experiment by the duration of the incident Nd:YAG pump pulse.

The rapid decrease in probe transmission is probably the result of absorption and scattering from the laser induced plasma and has been termed plasma shielding. It is important to note, however, that the plasma shielding should last only for several nanoseconds, a time comparable to the plasma lifetime. In contrast, Figure 2c shows that the probe transmission does not recover on this time scale. Additional experimental measurements indicate that the probe transmission in fact remains reduced for about 100 μs. This effect may be attributed to cavitation or gas bubble formation. The probe is scattered by a gas bubble which develops at the breakdown site. Transmission occurs only after the bubble has collapsed or broken up and the saline solution has returned to its unperturbed state.

The details of these physical processes may be further elucidated by performing spatially resolved pump-
On a microsecond time scale (Figure 3b), the probe beam transmission is observed to become almost completely zero for times between 8 µs and ~90 µs after the initiation of the breakdown. This is the result of a gas bubble which is generated at the breakdown site, expands radially outward, then collapses. When the optical breakdown occurs, the gas-liquid phase front is generated and begins expansion. The probe beam transmission is unaffected until this phase front crosses the probe beam focal point at 8 µs. For times between 8 µs and ~90 µs the gas bubble radius is larger than 250 µm and the gas-liquid phase front scatters the probe beam. The bubble then collapses, and probe transmission is restored when the bubble radius becomes less than 250 µm.

A systematic set of time-resolved measurements as a function of spatial separation between the pump and probe beams allows the detailed characterization of the transient temporal and spatial properties of the plasma, acoustic wave, and cavitation which accompany the laser induced breakdown process. The physical dimensions and propagation velocities associated with these phenomena may be measured to construct a detailed dynamical description.

The behavior of the acoustic transient was investigated by measuring the arrival time of the acoustic transient at given distances from the breakdown origin. Figures 4a and 4b show experimental measurements of acoustic wave propagation obtained with Nd:YAG pump laser pulse energies of 10 and 20 mJ. The acoustic wave is generated at the breakdown site and propagates radially outward as a shock wave with an initial hypersonic velocity. As the wave front expands it loses energy and propagates at a constant velocity. For a pump pulse energy of 10 mJ, the initial velocity of the shock wave is ~2100 m/s. After propagating approximately 100 µm in ~50 ns, the acoustic wave velocity decreases to ~1700 m/s and remains constant thereafter. This is in reasonable agreement with the velocity of sound in water of ~1500 m/s. Increasing the pump laser pulse energy results in a more rapid initial shock wave velocity as well as an increase in the size of the nonlinear propagation or shock wave region. Measurements of the plasma absorption performed at initial times of 10–20 ns as a function of distance indicate that the initial radius of the breakdown region is ~10 µm and ~25 µm with 10 mJ and 20 mJ pulses respectively.

Experimental measurement of the cavitation or gas bubble formation and collapse may be performed by determining the onset and recovery times of the probe beam scattering on a microsecond time scale. Figures 5a and 5b show data obtained for pump pulse energies of 10 mJ and 20 mJ respectively. For a pulse energy...
of 10 mJ, the gas-liquid phase front expands radially outward with an initial velocity greater than 50 m/s. The expansion velocity then slows rapidly after the first 10 μs. The maximum bubble radius of ~500 μm is reached at ~60 μs and is followed by a collapse of the bubble with a velocity of ~11 m/s. The expansion velocity, maximum size, and temporal duration of the bubble increase with increasing pump pulse energy.

The error bars on the data are the result of fluctuations in the cavitation process which occur with successive laser shots and are not due to electronic or instrumental limitations in time resolution. The dynamics of the bubble collapse are relatively unstable and precise measurements are difficult; however, the expansion phase of the cavitation may be well characterized. The use of unfiltered saline solution which had a higher concentration of small particle impurities and gas bubbles resulted in a decrease in the threshold for laser-induced breakdown as well as a decrease in the shot to shot fluctuations in the dynamics of the breakdown process. The dimensions and propagation velocities associated with the acoustic transient cavitation also increase for unfiltered or impure solutions.

**Discussion**

These results define some of the clinically relevant damage mechanisms involved in the photodisruption of ocular structures with short pulsed Nd:YAG lasers. The dynamic behavior of the processes which accompany laser-induced optical breakdown may be summarized as follows: When the laser pulse interacts with the material, it first generates a laser-induced plasma via local heating and/or nonlinear absorption. This plasma causes an increased absorption and scattering of the incident laser energy which gives rise to the plasma shielding effect. The dynamics of the plasma generation occur on a subnano-
second time scale and are too rapid to be resolved in this experiment. The dimensions of the plasma may be determined by measuring the absorption region. As expected, the size of the plasma increases with increasing laser pulse energy or the presence of impurities in the solution. Measurements of the temporal behavior of the plasma luminescence indicate that the plasma decays by radiative emission, spatial expansion, and heating of the surrounding solution on a time scale of several nanoseconds. This expansion of the plasma and/or the heating of the solution generates a pressure wave which propagates radially away from the breakdown region. The wave exhibits an initial nonlinear behavior and propagates with a hypersonic velocity, then expands and loses energy to enter the linear regime. Thereafter it propagates with the velocity of sound. The heating of the solution also produces a gas-liquid phase change and gives rise to cavitation or gas bubble formation. The gas bubble expands rapidly for several microseconds, then slows to reach its maximum size, and finally collapses.

The hypersonic acoustic transient velocity as well as the velocity of the gas bubble and its dimensions increases with increasing laser pulse energy. This observation explains, in part, the increasing severity of tissue alterations observed in the eye with photodisruption at higher pulse energies. The presence of impurities in the target solution causes an increase in the shot to shot stability of the laser induced breakdown process as well as a decrease in the breakdown threshold and an enhancement of the hypersonic acoustic transient and gas bubble formation. This is in agreement with previous investigations which hypothesize that the breakdown process is initiated by the heating of impurities in the liquid. In summary, this research has demonstrated the application of time-resolved spectroscopic techniques for the investigation of Nd:YAG laser-induced optical breakdown in a saline model. The use of a spatially resolved pump-probe technique has been shown to allow the measurement of both spatial and temporal behavior so that a description of the physical dimensions, propagation velocities, and dynamical behavior of the laser-induced breakdown may be obtained. Thus, plasma formation and shielding, acoustic transients, and cavitation phenomena have been measured within a simple and consistent experimental context. This capability is useful for comparative or quantitative investigations of laser-induced breakdown. For example, further studies may be able to resolve questions regarding differences in the physical processes and damage mechanisms associated with Q-switched versus modelocked Nd:YAG ophthalmic laser surgery. An increased understanding of the transient phenomena associated with laser-induced breakdown not only is important to ophthalmic applications but also is relevant in the context of recent studies which indicate the presence of acoustic and localized vaporization mechanisms for pulsed laser interaction with pigmented structures, cells, or organelles. We believe that time-resolved spectroscopic techniques will become increasingly important in the experimental investigation of laser tissue interactions in general and will prove especially useful with the development of laser medical techniques using pulsed laser sources.

Key words: Nd:YAG, laser-induced breakdown, plasma shielding, photo disruption

References