Shielding Properties of Laser-Induced Plasmas in Ocular Media Irradiated by Single Nd:YAG Pulses of Different Durations

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Shielding of laser pulses by plasmas generated in ocular media has been experimentally investigated using single Nd:YAG laser pulses of different durations, ranging from several nanoseconds (ns) to a few tens of picoseconds (ps), both in saline solution and extracted calf vitreous. At the respective threshold radiant exposures for breakdown in saline (259 mJ/cm² for 7 ns, 20.5 mJ/cm² for 220 ps and 4.7 mJ/cm² for 30 ps pulses) the single pulse energy transmission is found to be about 74% for 7 ns, 55% for 220 ps and 50% for 30 ps, thus showing that shielding of laser-induced plasmas is more effective for shorter pulses than for longer pulses. Moreover, the decrease in transmission with increasing radiant exposure is faster in the picosecond case than in the nanosecond case. These results show that direct irradiation of the retina is, to some extent, present especially near threshold. In the case of picosecond pulses, a comparison with published results indicates that shielding between subsequent pulses in a train is likely to occur only to a very limited extent. Invest Ophthalmol Vis Sci 29:437-443, 1988

The role of the laser-induced plasma in shielding the retina from the high irradiance of the laser pulse itself during posterior capsulotomy or vitreal surgery is of great concern to the clinical ophthalmologist, who usually exerts great care in setting the laser parameters as close as possible to the threshold for photodisruption.1-3 However, the information available on plasma shielding is presently derived mainly from studies of plasmas in gases4-5 and in solids,6-7 but not in liquids, while empirical evaluations have been done by comparing the performances of commercial lasers.8-9 This information can lead to an oversimplification of the problem.

There exists a profound difference between the two laser sources commonly used for ophthalmic microsurgery: the Nd:YAG lasers in either the Q-switched (single pulses with duration of ~10 ns) or the mode-locked (multiple pulses of duration of 30 ps each) operation. This difference also reflects, of course, on the physical aspects of the disruption procedure.

The aim of this paper is to compare the phenomenon of plasma shielding produced by nanosecond (ns) and picosecond (ps) pulses. This effect has been studied with single pulses of 7 ns, 220 ps and 30 ps generated by Nd:YAG lasers. The results shown are closely connected to those reported in a previous paper10 that deals with comparative threshold studies of optical breakdown in liquids commonly used in ocular models. Basic differences between the intra-pulse shielding effect occurring with the mentioned pulses will be examined, and some clinical implications discussed.

Materials and Methods

The experimental apparatus used to perform the shielding experiments is shown in Figure 1. The laser beam was expanded and then focused into the cell containing the liquids of interest, ie saline solution and extracted calf vitreous. An image of the focal spot was created at the detector site. The diameter of the imaging lens was chosen in such a way as to collect only the light transmitted or scattered from the plasma within the cone angle of the input beam. Therefore, no apertures or pinholes were needed at the detector location to discriminate this light against scattering at larger angles.

Shielding experiments with 7 ns pulses were performed with: (1) a passively Q-switched Nd:YAG laser developed in our laboratory1; the emitted beam presents a rather uniform spatial and temporal energy distribution even in the multimode configuration; (2) an energy meter (Gentec ED 200; Ste. Foy, Quebec) to monitor the energy of the transmitted pulse; and (3) a vacuum photodiode (CDC Mod. 105) connected

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Fig. 1. Schematic diagram of the experimental apparatus for shielding experiments. FL: focusing lens of focal length \( f_1 \); QC: quartz cuvette; IL: imaging lens of focal length \( f_2 \); \( \theta \): semiaperture of the focusing cone angle; D: detector.

to a storage oscilloscope to monitor the temporal shape.

Shielding experiments with picosecond pulses were performed using: (1) an actively-passively mode-locked Nd:YAG laser system (Quantel Mod. 402; Les Ulis, France), consisting of an oscillator and of two amplifiers, which generated single 220 ± 5 and 30 ± 3 picosecond pulses with a TEM_{00} mode; (2) a calorimeter (Scientech Mod. 362 with 380181 head; Boulder, CO) to monitor the transmitted energy; and (3) a streak camera (Hamamatsu Mod. C979; Bridgewater, NJ) having a temporal resolution of 11 ps connected to a computer, to monitor the temporal shape of the pulses.

The laser pulses were focused into the cell using quartz lenses of suitable focal lengths. The irradiance in the focal plane was calculated by dividing the input pulse energy by the pulse duration and by the area of the focal spot.

The setting of the pulse energy for shielding experiments required accurate measurements of the optical breakdown (OBD) probability curves in our experimental conditions. OBD curves express the probability of occurrence of the breakdown phenomenon as a function of the input irradiance; they have been obtained by finely adjusting the pulse energy and by monitoring, at each energy, the number of breakdown events over a preset number of pulses delivered to the medium.

In the case of 220 and 30 ps pulsewidths, shielding experiments were performed, and OBD curves obtained, also using the second harmonic of the laser wavelength at 532 nm, since the streak camera was insensitive to the radiation at the fundamental wavelength. The consistency of the data obtained at 532 nm with those at 1,064 nm was checked in this way: for both wavelengths, we measured the overall energy transmission from the plasma region at several points in the OBD curve. We took into account that OBD thresholds and also the slopes of the curves differ when going from 1,064 nm to 532 nm, as expected.\(^7\)

Since the two transmission curves turned out to be practically the same, we were confident that the pulse shape obtained at 532 nm could be significative of that obtained at 1,064 nm.

Results

A set of optical breakdown curves obtained in saline under irradiation with pulses of different pulse-widths and wavelengths is shown in Figure 2a; Table 1 summarizes some of the parameters which characterize these curves. OBD curves are known to vary with the duration of the laser pulse, as well as with the focusing conditions of the beam.\(^9,^{10,12}\) An important parameter of an OBD curve is the slope, which gives an indication of the statistical nature of the breakdown process under irradiation with a given pulsewidth. We plotted in Figure 2b the set of OBD curves of Figure 2a, in a normalized way (the abscissa being expressed as the ratio of the irradiance \( I \) to the threshold irradiance \( I_{th} \)), and in a simplified form—curves below threshold have been substituted by straight lines with a slope equal to the slope of the curve as defined by:

\[
0.5 \times I_{th,100\%} \times \left( \frac{I_{th,100\%} - I_{th,50\%}}{100\%} \right)^{-1}
\]  

Typical temporal behavior of laser pulses transmitted through the plasma region in the three conditions of 7 ns, 200 ps and 30 ps pulsewidth are illustrated in Figures 3a, 4a and 5a, respectively. In all three cases the highest curve represents the temporal shape of the pulse in the absence of breakdown; the others show the temporal shape of the transmitted pulses at different incident irradiances. In each case the peak amplitude of the pulse was normalized to reproduce, in the absence of breakdown, that of the highest pulse. Figures 3b, 4b and 5b show, in each situation, the transient transmission of the plasma, ie the ratio of the transmitted to the incident irradiance at each time within the pulse.

By comparing the set of Figures 3a, 4a and 5a, we note that, at a given value of \( I/I_{th} \), the shielding becomes more effective as the pulse duration is decreased. Moreover, from the set of Figures 3, 4 and 5 it can be noted that the onset of shielding occurs within the first half of the pulse. Shielding with picosecond pulses starts earlier than that with nanosecond pulses at equal \( I/I_{th} \) ratios. Starting times for shielding are seen to occur earlier by increasing the irradiance;
Table 1. Summary of the optical breakdown threshold measurements for saline (S/V ratio = 80)\textsuperscript{10}

<table>
<thead>
<tr>
<th>Pulsewidth (ps)</th>
<th>Wavelength (nm)</th>
<th>( I_\text{th} \times 10^{10} ) W/cm(^2)</th>
<th>( R_\text{th} ) J/cm(^2)</th>
<th>( \Delta I/I_\text{th} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7000</td>
<td>1064</td>
<td>3.40</td>
<td>236</td>
<td>32.4</td>
</tr>
<tr>
<td>220</td>
<td>1064</td>
<td>9.19</td>
<td>20.5</td>
<td>21.1</td>
</tr>
<tr>
<td>220</td>
<td>532</td>
<td>14.08</td>
<td>31.4</td>
<td>25.2</td>
</tr>
<tr>
<td>30</td>
<td>1064</td>
<td>14.60</td>
<td>4.67</td>
<td>20.47</td>
</tr>
<tr>
<td>30</td>
<td>532</td>
<td>19.38</td>
<td>6.20</td>
<td>22.20</td>
</tr>
</tbody>
</table>

breakdown (at 100\% probability) for the 7 ns, 200 ps and 30 ps duration, respectively (at 1,064 nm), as reported in Table 1. The shaded area at the left of

however, this trend is more marked with nanosecond pulses than with picosecond pulses. Moreover, the asymmetry of the transmitted pulse is more enhanced in the nanosecond regime.

Figure 6 shows curves of transmitted irradiance vs. input irradiance of the laser beam for the three pulse durations considered. Of course, when the breakdown probability was <100\% (ie \(I < I_\text{th}\)), the transmitted irradiance was measured only when breakdown did occur. In Figure 6, the straight line is then 100\% irradiance transmission curve; we have indicated with \(I_1\), \(I_2\) and \(I_3\) the threshold irradiance values for

Fig. 3. Shielding effect of plasmas induced in saline by 7 ns laser pulses. (a) Temporal behavior of the pulses. (b) Time-resolved transmission. From upper to lower curve: unshielded pulse, \(I = I_\text{th}\), \(I = 2 \times I_\text{th}\).
corresponding to 7 ns pulses. In fact, they are characterized by an abrupt decrease in the transmitted intensity, thus showing a higher shielding effect given by shorter pulses. Furthermore, the transmission at threshold and at twice the threshold value is lower than in the case of nanosecond pulses. At threshold they are about 50% and 41% for 220 and 30 ps, respectively, and at twice the threshold intensity they decrease to 20% and 15%, respectively. The sharp transition between the linear-transmission region and the shielding region reflects the high slope of the breakdown curve (defined by Eq. (1)) shown in Figure 2; in fact, the irradiance interval corresponding to the 0–100% breakdown probability is percentually narrower for picosecond pulses than for nanosecond pulses.

As a comment on these curves, we note that the transmission curve in the case of nanosecond pulses shows a smooth change from full transmission (straight line) to partial transmission with increasing input intensity. The amount of shielding is seen to increase from the low value corresponding to intensities below threshold. A plateau in the output intensity has been found at input intensities corresponding to about three times the threshold value. Numerical values for the transmission factor are about 57% at threshold (37 GW/cm²) and 33% at twice the threshold (74 GW/cm²).

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Figure 7 gives a similar representation for the radiant exposure. A log-log plot has been given since the threshold values for this quantity vary by about two orders of magnitude from nanosecond to picosecond pulses (Table 1); in contrast, the variation of OBD irradiance with pulsewidth is within only one order of magnitude. As in Figure 6, threshold values for the radiant exposure and shaded regions for breakdown occurrence are shown. Since the beam spot size is the same with all the pulse durations, the absolute energies can also be given on the same axis. Their values, however, can be referred only to the specific experimental conditions (pulse durations and beam focusing) used in this work. From Figure 7 it can be seen that the transmitted energy increases with input energy in the case of nanosecond pulses and also, although less markedly, in the case of 220 ps. In contrast, with 30 ps, the output vs. input curve is practically constant, or slightly decreases when input radiant exposure is increased.

Discussion

The previous experimental results show the effect in ocular media of the laser-induced plasma on the laser pulse itself. The corresponding shielding of the retina from direct laser irradiation is, of course, of clinical relevance.

A preliminary aspect related to our experiments concerns the choice of our models as representative of the clinical situation. The clear, impurity-free media like distilled water and fresh vitreous used in these experiments may not appear adequate to suitably simulate opacified membranes or vitreal strands. However, previous experiments carried out on liquids and membranes with nanosecond pulses indicated that, under single pulse irradiation, the fraction of transmitted light to incident light is approximately the same for distilled water and polythene membranes, and other authors' studies indicate that the same holds for trains of mode-locked pulses. In the case of thickened membranes or structures with high linear absorption and the laser wavelength the situation may well be different; in this case, however, no simple physical model would be adequate to study the dynamics of plasma formation and evolution in these structures.

A first comment is related to the dependence of threshold irradiance and radiant exposure on the pulsewidth, as shown in Figure 2 and Table 1. This dependence is closely related to the dynamics of the breakdown formation and evolution in liquids. In a previous paper we showed that the laser-induced breakdown in liquids is likely produced by the same mechanism which occurs in solids. A higher threshold irradiance is required with shorter pulses due to the shorter interaction time between the laser pulse and the medium.
Concerning the temporal shape of the transmitted pulses, we first observe that, unlike the case of pure solids, in liquids the transmitted pulses experience a gradual decrease in amplitude even at energy values well above the breakdown threshold, rather than a sharp cut. These pulse shapes, obtained in situations of rather tight focusing, resemble those reported in the case of impure crystals. A second observation refers to the transient nature of the absorption. As expected, the starting instant of plasma absorption shifts towards the beginning of the pulse as the input irradiance is increased. This has been observed with all three pulsewidths examined, but the effect is more evident with longer pulses. However, there is evidence from the comparison of Figures 3b, 4b and 5b that in the case of nanosecond pulses the absorption lasts longer than the excitation pulse duration, while with picosecond pulses the absorptive condition is seen to terminate with the pulse. Our findings with nanosecond pulses confirm those reported by others using pump-and-probe experiments, while at the moment there are no other experimental data available in the literature on picosecond intrapulse shielding in liquids under single pulse irradiation.

From a clinical viewpoint, these results indicate that temporal shaping of the laser pulse, as proposed, could lead to a more effective laser disruption procedure. The combined effect of a subnanosecond initial transient to immediately establish the plasma, followed by a plateau of nanosecond duration to maintain the absorptive regime, could in fact maximize the conversion of the laser light into the mechanical energy required to disrupt the target and to minimize transmission.

We now discuss the effect of shielding in terms of transmitted irradiance (vs. input irradiance) and radiant exposure (vs. input radiant exposure) as represented in Figures 6 and 7. Our results first indicate that in all the considered cases the fraction of incident light that is transmitted or scattered within the cone angle of the incident beam is still very high when the laser pulse is around threshold. In the case of nanosecond pulses, the transmitted energy density increases as the input increases up to approximately three times the threshold value. These findings agree well with those obtained by Steinert et al with commercial, single-pulse, ophthalmic disruptors. From a clinical standpoint, in these conditions the shielding effect with nanosecond pulses cannot be considered beneficial for safety purposes.

Our results show also that shielding with single picosecond pulses is indeed more effective than with nanosecond pulses, even near threshold. In fact, the transmitted energy density first decreases then remains almost stationary as the input increases up to approximately three times the threshold. In comparison with nanosecond pulses, therefore, single picosecond pulses give an irradiation of the retina characterized by a higher irradiance (by a factor 2.5–3 near threshold, in our case), but also by a much lower radiant exposure (by a factor 25–30 near threshold, in our case). Whether their use results in a safer procedure depends on the still unanswered basic question: whether retinal damage is decreased due to the strong decrease in radiant exposure or rather increased due to the simultaneous, moderate increase in irradiance. However, it is to be noted that all the mode-locked laser disruptors commercially available do not generate a single pulse but rather a train of approximately ten short pulses with a periodicity of ~3 ns. In this case, two points should be considered: (1) only a fraction of the pulses have energy enough to produce breakdown; and (2) interpulse shielding, ie, shielding of a pulse by plasmas obtained by previous pulses, can be present. For a characterization of the latter effect measurements of the lifetime of the plasma and of the typical perturbations induced in the liquid by shock or acoustic transients with picosecond pulses would be required. However, a simple comparison of our transmission curve for single picosecond pulses with that referred to the entire train, reported by Steinert et al for pulse trains, indicates that shielding in the latter case is less effective than in the former case. This would support the hypothesis that no, or only little interpulse shielding occurs in mode-locked trains.

Finally, it would be important to relate the extent of laser shielding to the plasma length for a range of irradiance values. Longer plasmas could be potentially more harmful than shorter ones to surrounding tissues, especially when disruption occurs in the posterior vitreous close to the retinal surface.

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

Acknowledgments

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References

2. Steinert RF and Pulaflito CA: Retinal protection. In YAG


