Freeze frame analysis on high speed cinematography of Nd/YAG laser explosions in ocular tissues

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SUMMARY High speed colour cinematography at 400 frames per second was used to photograph both single and train burst Nd/YAG laser applications in ox eyes at threshold energy levels. Measurements of the extent and speed of particle scatter and tissue distortion from the acoustic transient were made from a sequential freeze frame analysis of the films. Particles were observed to travel over 8 mm from the site of Nd/YAG application 20 milliseconds after a single pulse at initial speeds in excess of 20 km/h. The use of train bursts of pulses was seen to increase the number of particles scattered and project the wavefront of particles further from the point of laser application.

In recent years the use of the Nd/YAG laser has gained wide acceptance in anterior segment surgery.¹ To observe the events occurring immediately following the optical breakdown phenomenon, we filmed the action of the Nd/YAG laser in an ox eye using high speed cinematography. At a film speed of 400 frames per second we observed particulate dispersion and tissue distortions in the first few milliseconds following plasma formation.

Plasma formation and the acoustic transient it generates occur only when the energy applied is at or above a threshold which varies with the molecular composition of the target.² Observation of threshold pulses will therefore give a guide to the minimum effects to be expected during clinical use.

Material and methods

The short pulsed, Q switched Nd/YAG laser photo-disrupter used in this study was a Lasag Sirius Microruptor II.

Fresh ox eyes were mounted so that the helium/neon aiming beams of the laser could focus via the central cornea on the anterior lens capsule and iris respectively. The eyes were maintained in a moist condition for filming by the frequent application of methyl cellulose drops. Contact lenses were not used during the study for laser focusing, as their use would have interfered with filming. Adequate lighting was obtained by condensing a 2 kW tungsten halogen light using a system of lenses.

With the camera running at 400 frames per second predetermined threshold pulses were delivered while the laser aiming beams were focused on the anterior lens capsule (2.4 mJ) and iris (2.9 mJ) just below the pupil margin. A train of five pulses of 2.9 mJ per pulse at 20 millisecond intervals was then applied to the iris. The film was subjected to freeze frame analysis by projecting individual 16 mm frames on to a screen and measurements of particle scatter and tissue displacement were made. These were converted to real values from direct proportional data.

Graphs of particle displacement against time were constructed from the knowledge that the camera shutter opens for 1/1200 second per frame at a film speed of 400 frames per second and is closed for 1/600 second between frames.

Results

In the first frame showing observable events following a threshold pulse of 2.4 mJ applied to the capsule the shockwave had already scattered bubbles and particles 3-78 mm from the target point (Fig. 1). The exact timing of the 12 nanosecond pulse could not be determined even at a film speed of 400 frames per second and could have occurred at any point following the closure of the shutter from the previous frame. The maximum time for the measured initial particle displacement was 1/400 s, indicating a minimum mean particle velocity of 1.5 m/s (5.4 km/h) in the first few milliseconds following plasma formation.

Fig. 2 shows the rapid deceleration in particle

Fig. 1 First frame following 2.4 mJ application to capsule.

velocity occurring over the subsequent 20 milliseconds.

Particulate scatter was more easily observed after laser application to the iris. An intense white light was sometimes seen at the target centre in the frame coinciding with new observable events following each YAG pulse (first frame) (Fig. 3). This white light was distinct in contrast, tone, and position from the rapidly advancing wavefront of particles and was not observable in the next frame less than 1/400 second later (Fig. 4). However, other features related to the acoustic transient could be traced in subsequent frames as the wavefront progressed. Serial observa-

Fig. 2 Distance of bubbles from target plotted against time for single shot on capsule.

Fig. 3 First frame following 2.9 mJ application to iris. Note white light and cloud of particles above.

tions of all applications showed that this white light was present in 43% of first frames.

Measurements of the wavefront from a single application of 2.9 mJ to the iris showed a similar deceleration in particle velocity during the first 20 milliseconds following plasma formation (Fig. 5). A maximum time for initial particle displacement was again 1/400 s, resulting in a minimum mean initial velocity of 0.93 m/s (3.4 km/h). The particle displacement of 11.62 mm occurring at 100 milliseconds following laser application was the maximum observed before convection currents altered the linear dispersion of the particles (Fig. 6).

Particle scatter after the application of a train of pulses of 2.9 mJ each of which was separated by 20 milliseconds showed similar initial velocities and rate of decline (Fig. 7). However, succeeding pulses briefly increased the declining particle velocity and projected initial particles further from the target point while creating a new cloud of particles (Fig. 8).

Rapid tissue displacement was also observed by noting the acute anterior displacement of the iris

Fig. 4 Second frame, single iris shot, 1/400 second after Fig. 3.

Fig. 5 Distance travelled by particles per unit time for single shot on iris.

(Figs. 3 and 8) with a peak to trough distance of 1.44 mm measured in the 'first frame'.

The cumulative effect of a train of five pulses in terms of the quantity of particles was observed on viewing the frame coinciding with the fifth pulse, 100 milliseconds following the first pulse (Fig. 9).

The film speed of 400 frames per second was verified, as pulses at 20-millisecond intervals were separated by eight frames on analysis.

Discussion

The cutting effect produced by the Nd/YAG laser results from events during and immediately following plasma formation. A rapidly expanding plasma volume at high temperature (approx. 10 000°C) produces an acoustic transient which generates a shock wave mechanically disrupting tissues round the target

centre.² These processes are necessary to produce the desired 'cutting' action but are accompanied by certain effects which may be undesirable. These include the ultraviolet light emitted by the plasma, acoustic shock waves, electromagnetic field stress, thermal conduction, the residual YAG energy past the point of optical breakdown, free tissue debris which may occlude drainage channels, and high velocity particle scattering.

Initial reports of complications subsequent to the clinical use of Nd/YAG lasers concentrated on the incidence of raised intraocular pressures, usually of a transient nature, and even suggested that there was no significant risk to the endothelium.^{3,4} Emphasis in animal models has been placed on endothelial damage from the direct mechanical effect of the Nd/YAG shock waves,⁵ and it has been suggested that peripheral iridotomies performed at a distance of >1 mm from the endothelium would be expected to produce no acute corneal endothelial damage.⁶

Vitreous collapse with anterior vitreous liquefaction and posterior vitreous detachment has been associated with retinal breaks and subsequent detachments following YAG laser capsulotomy.⁷

Until recently little mention had been made of the potentially damaging effects of high velocity particle scattering. Kerr-Muir and Sherrard suggest that the endothelial changes observed following Nd/YAG laser iridotomies and capsulotomies are likely to be due to particle bombardment of the endothelium, as endothelial damage occurred in quadrants remote from the target point.⁸ Their patients received treatments consisting of 1–20 bursts of up to 3–4 pulses per burst using energies up to 12.5 mJ per pulse—that is, well above threshold levels.

Our study shows that, even with threshold energy,

Fig. 6 Particulate dispersion 100 milliseconds following single 2.9 mJ laser application to iris.

Fig. 7 Distance travelled by particles plotted against time for train burst on iris.

high velocity particles are produced which may travel over 8 mm in the first 20 milliseconds after the application of a single pulse. Compared with single pulses, train pulses clearly create more particles, which are projected further from the target point so quickly as to be hardly discernible to the naked eye.

Even with a film speed of 400 frames per second the exact timing of a 12-nanosecond pulse cannot be determined, and therefore the mean initial velocities above are likely to be an underestimate. We believe the white light observed in the 'first frames' to be the spark emitted as free electrons and ions recombine following plasma formation as in a lightning bolt or static electricity discharge.²

As the plasma is estimated to emit light for twice the pulse duration (that is, 24 nanoseconds),⁹ any observation of a spark in a single film frame implies that plasma formation occurred during that 1/1200 second. The camera shutter is open for $\frac{1}{3}$ of the total filming time and therefore on average 33% of YAG pulses would be expected to coincide with the interval when the shutter is open. An observed incidence of the white light in 43% of first frames would be in line with this order of probability.

If plasma formation can be accepted as occurring within the 1/1200 second recorded by a single frame, the minimum mean initial velocity of particles from the single iris pulse is 2.78 m/s (10.0 km/h). This

Fig. 8 Frame coinciding with second pulse during train burst on iris. Note white light above iris furrow with dense new cloud of particles at pupil margin.

Fig. 9 Frame coinciding with fifth pulse in train burst on iris, 100 milliseconds following first pulse.

figure assumes the pulse to be delivered immediately on the opening of the camera shutter.

Measurements of wave front distances in first frames including the white light phenomenon do not differ significantly from that recorded from the single iris pulse. Therefore, if the YAG pulse can be presumed to be delivered at the midpoint of the frame, the mean particle velocity in the first millisecond following plasma formation is 5.56 m/s (20.0 km/h).

In performing peripheral iridectomies the site chosen usually has an iris to cornea distance of <2 mm. A single threshold pulse will produce particles which may impact with the endothelium within a millisecond of plasma formation. These particles may be travelling at speeds in excess of 20 km/h and clearly would be expected to produce observable effects on specular microscopy.

New applications for the Nd/YAG laser are being reported with as many as 300–500 bursts being advocated for certain procedures.¹⁰ The potential harm from tissue distortion as well as endothelial and trabecular meshwork damage from high velocity particles should be considered when investigating clinical applications for the Nd/YAG laser, particularly on compromised eyes.

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