
Ocular hazards of the Q-switched erbium laser

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The threshold for ocular damage was determined in owl monkeys with the use of a Q-switched erbium-glass laser at 1.54μ constructed in the laboratory. Ocular damage was limited to the cornea and characterized by localized opacification of the epithelium and stroma. All exposures to energy densities greater than 30 j./cm.^2 produced injury. The median level for damage occurred at 21 j./cm.^2 , and no injury could be detected below 17 j./cm.^2 . Comparison with threshold values for ocular damage by Q-switched lasers operating in the visible and near visible portion of the spectrum shows that the erbium laser offers promise as a relatively "safe laser."

Key words: necrosis of cornea due to radiation, radiation injury, radiation intensity, lasers, experimental results, histopathology, monkeys.

Because of the serious ocular threat posed by laser devices operating in the visible portions of the spectrum, less hazardous laser systems are being sought by both the civilian and military communities. One approach is to utilize lasers that operate in spectral regions where the ocular media are relatively opaque to the incident radiation. In this respect the erbium laser offers a theoretical advantage based upon its emission spectrum in the infra-red.¹ Depending upon the host material employed, the emission wavelength of erbium varies from 1.53μ in glass to 1.64μ in yttrium-aluminum-garnet. The transmission of the eye at the erbium wavelengths is quite low (Fig. 1). Based upon these considerations a series of experiments were conducted to study the ocular effects of the Q-switched erbium laser.

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Methods

An erbium laser was constructed in this laboratory to deliver Q-switched laser pulses at 1.54μ . The dearth of erbium laser rods of even moderately good quality seriously restricted the design technique. The resulting erbium-glass laser consistently delivered up to 100 mj. of Q-switched energy in a single 50 nsec. pulse. Between 100 and 200 mj. output double pulsing occasionally occurred, yielding two 50 nsec. pulses separated by 200 nsec. Because of the quality of the laser rod, the beam cross section was quite irregular.

An elliptical cavity was used to couple the linear flash lamp to the laser rod. Q-switching was accomplished by a rotating prism driven at 20,000 r.p.m. and electronically synchronized to the flash lamp. A three-element quartz resonant reflector with a reflectivity of 65 per cent was used as the output mirror. A sapphire optical flat inserted in the resonant cavity at the Brewster angle polarized the laser output. This was required because polarization-dependent beam splitters were used in the delivery-detection system. The separate components were mounted on an optical bench yielding a total resonator length of 50 cm. A pulse-forming network consisting of $1300\mu\text{f}$ capacitance in series with $850\mu\text{h}$ inductance provided a 3.5 msec. pulse through the flash lamp. Triggering was accomplished through an inline trigger transformer.

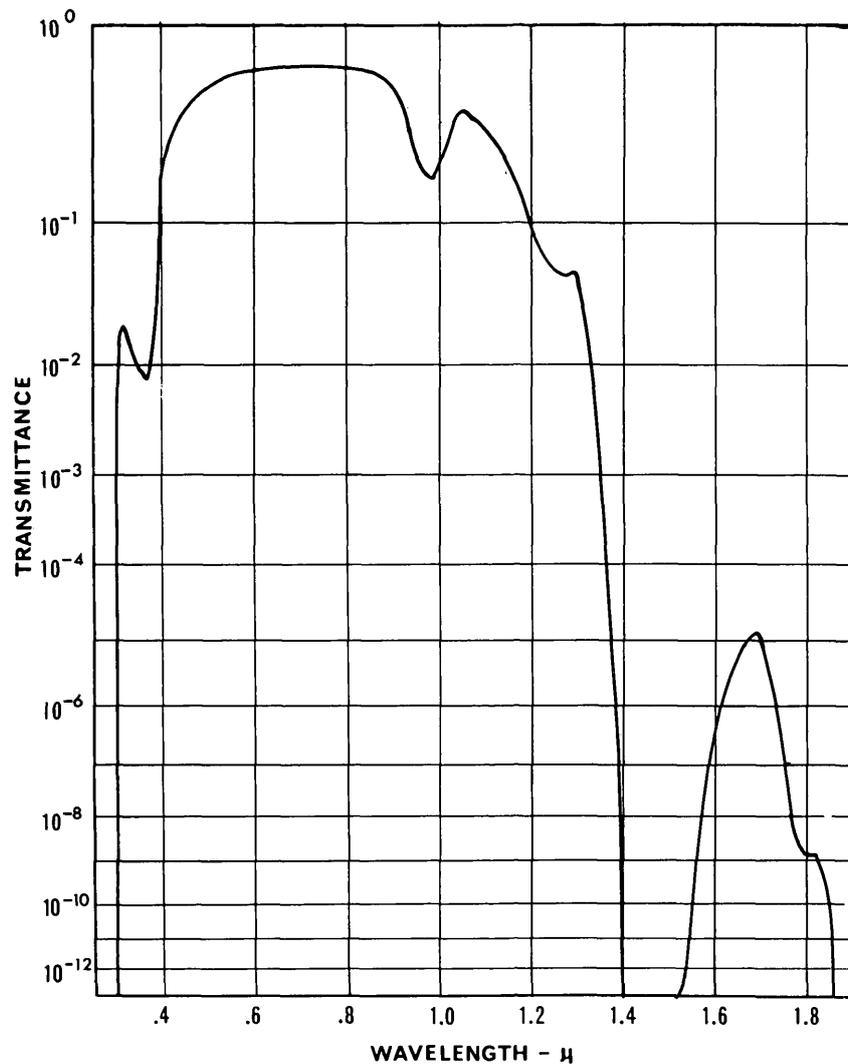


Fig. 1. Spectral transmittance through human eye. Between 0.3 and 1.3 μ , the curve is based on measurement of human ocular tissue² Beyond 1.3 μ , the transmittance is that of a 2.2 cm. layer of pure H₂O.

A detection system and a delivery system to couple the laser energy into the eye of the experimental animal were constructed as shown in Figs. 2 and 3. A low-power helium-neon laser beam was coupled into the delivery system through a beam splitter and carefully aligned to be colinear with the erbium laser beam, thus facilitating aiming and alignment of the system. After passing through attenuating and focusing optics, the erbium laser beam was limited by an aperture 2 mm. in diameter. Immediately beyond this aperture, a beam splitter directed a portion of the energy to a diffuse reflecting surface where it was monitored by calibrated detectors. An indium-

arsenide photodiode measured the duration and number of output pulses and a germanium photodiode with an integrating network measured the energy. The portion of the beam passing through the beam splitter was incident upon the cornea of the experimental animal. Calibration of the detection system was accomplished by placing a TRC 100 Ballistic Thermopile in the eye-exposure position and comparing the photodiode output to the thermopile output. This technique compensated for the peculiarities of the aperture, beam splitters, and detectors by utilizing them in calibration exactly as they were used in measurement. The calibration was checked immediately before

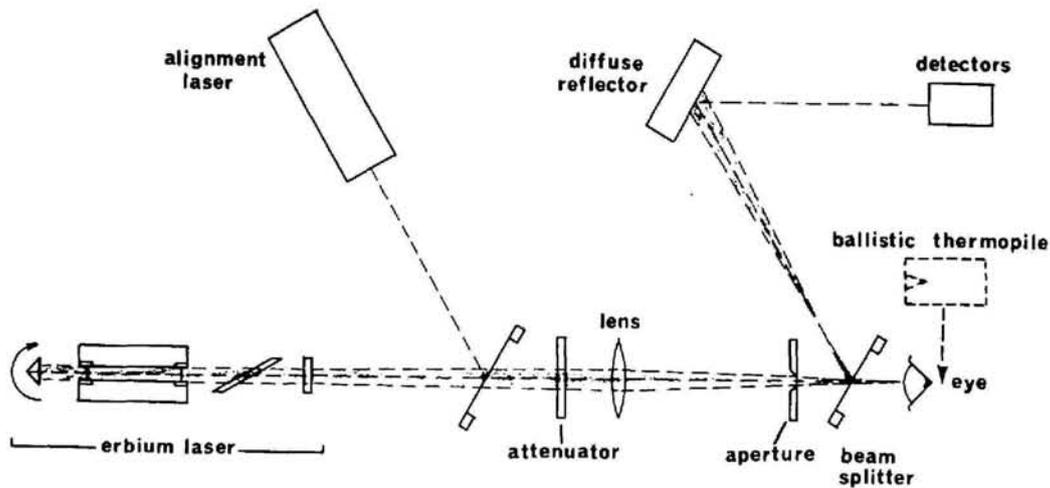


Fig. 2. Schematic diagram of the erbium experimental configuration.



Fig. 3. Erbium experimental apparatus showing owl monkey positioned for exposure.

and after each animal experiment, giving results reproducible to ± 10 per cent over the experimental period.

The animals used in these experiments were owl monkeys (*Aotus trivirgatus*). Preanesthetic medication consisted of a sedative dose of phen-cyclidine hydrochloride (0.25 mg. per kilogram) intramuscularly, and atropine sulfate (0.2 mg.) subcutaneously. Anesthesia was induced with sodium pentobarbital (approximately 5 mg. per

kilogram) via the saphenous vein. The pupils were dilated with phenylephrine hydrochloride (10 per cent) combined with cyclopentolate hydrochloride (1 per cent). Sutures of 3-0 silk were placed in the upper eyelids to facilitate their manipulation. Physiologic saline was used to prevent drying of the cornea.

Immediately before exposure, the eyes were carefully examined by slit lamp biomicroscopy and ophthalmoscopy, and any abnormal eye was

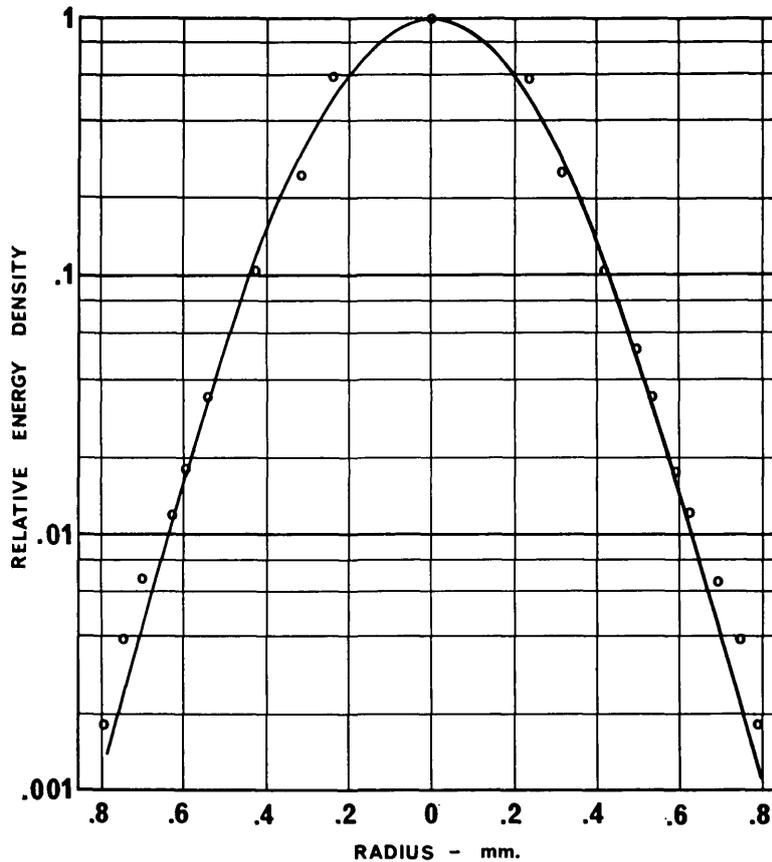


Fig. 4. Profile of the focused erbium laser beam showing experimental data points and a theoretical Gaussian curve.

rejected. The animal was placed in position in the delivery system and irradiated. Each corneal exposure site was examined immediately, and detailed biomicroscopy and ophthalmoscopy were performed at 30 to 60 minutes following exposure. Several eyes were observed at 1 day, 7 days, and 3 weeks following exposure.

Pathologic examination was performed on all eyes. The eyes were enucleated either immediately or from 1 to 14 days following exposure and fixed for 24 hours in 10 per cent formaldehyde. Serial sections of paraffin-embedded specimens were stained with hematoxylin and eosin and examined by light microscopy.

Two techniques of exposure were utilized. In the first series of experiments the direct output beam of the laser was employed without intervening optical lenses; a total of 15 exposures were placed in 5 eyes. In the second series of experiments a lens was used to focus the beam onto the cornea of the experimental animal for a total of 41 exposures in 14 eyes. In order to define the threshold level for damage, it was necessary to

determine the peak energy density within the focused beam. This posed the problem of measuring the characteristics of the beam cross section at the focus of the lens. A technique employing exposed Polaroid film was used for this purpose. When impacted by laser radiation, the emulsion was burned from the film where the laser energy density exceeded a certain value. The film was subjected to a series of exposures with the laser at constant output, but with the beam attenuated in step-wise fashion by calibrated neutral density filters. Measurement of the diameter of the progressively decreasing spot size allowed the relative energy density profile to be plotted (Fig. 4). The beam at the focus was found to be approximately Gaussian. If the beam is assumed to be Gaussian, it is possible to calculate the peak energy density. For the purpose of computation the diameter of the beam spot is taken to be that diameter at which the relative energy density falls to a value $1/e$ of the peak value. The peak energy density is then the total measured energy divided by the area of the spot so defined.



Fig. 5. Photograph of a fresh corneal lesion produced with the Q-switched erbium laser at 45 j./cm.². Note the localized opacification of the epithelium, Bowman's membrane, and stroma with radiating folds in Descemet's membrane.

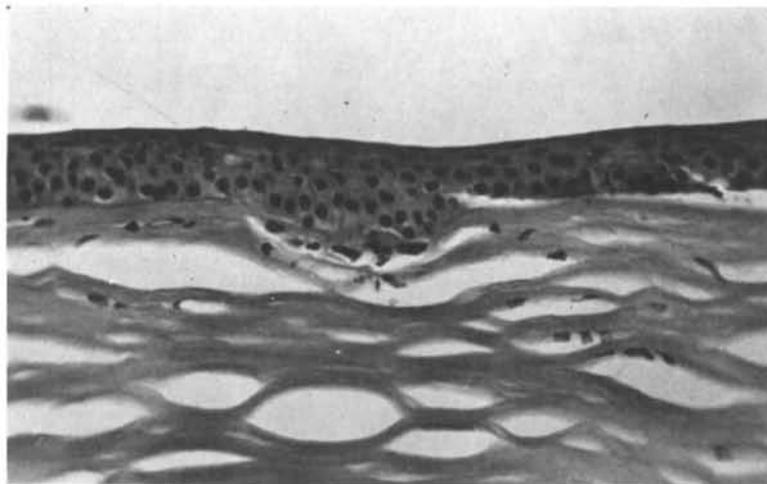


Fig. 6. Epithelial facet at the site of a healed 10-day-old corneal lesion. The anterior stroma contains fibroblasts and inflammatory cells. Separation of stromal lamellae is artifactitious. (Hematoxylin and eosin; $\times 500$.)

Results

In the first series of exposures using the direct output beam of the laser, corneal energy densities ranging from 0.1 to 1.0 j./cm.² were achieved. No evidence of corneal, lenticular, or chorioretinal injury could be detected at these energy levels. In the subsequent series of exposures with the laser beam focused at the cornea, ocular damage occurred and was limited to the cornea.

The minimum criterion for damage was defined as the presence of a corneal lesion seen by slit lamp biomicroscopy at 60 minutes following exposure. Near-threshold corneal lesions were characterized by a shallow depression of the epithelial surface with localized epithelial edema and mild fluorescein staining. Discrete grayish opaci-

fications of Bowman's membrane and the anterior corneal lamellae occurred at the impact site. More severe lesions showed a whiter opacification down to the deeper stromal layers and, in some cases, wrinkling of Descemet's membrane (Fig. 5). No lens or fundus changes were noted, and anterior chamber reaction was absent. The epithelial defects healed in the course of 1 to 3 days, while the stromal opacification remained essentially unchanged at the end of 3 weeks.

In fresh corneal lesions the histopathologic changes were characterized by localized coagulation necrosis of the epithelium, Bowman's membrane, and anterior stromal layers. Healed lesions showed proliferation of the corneal epithelium and the formation of collagenous scar tissue in

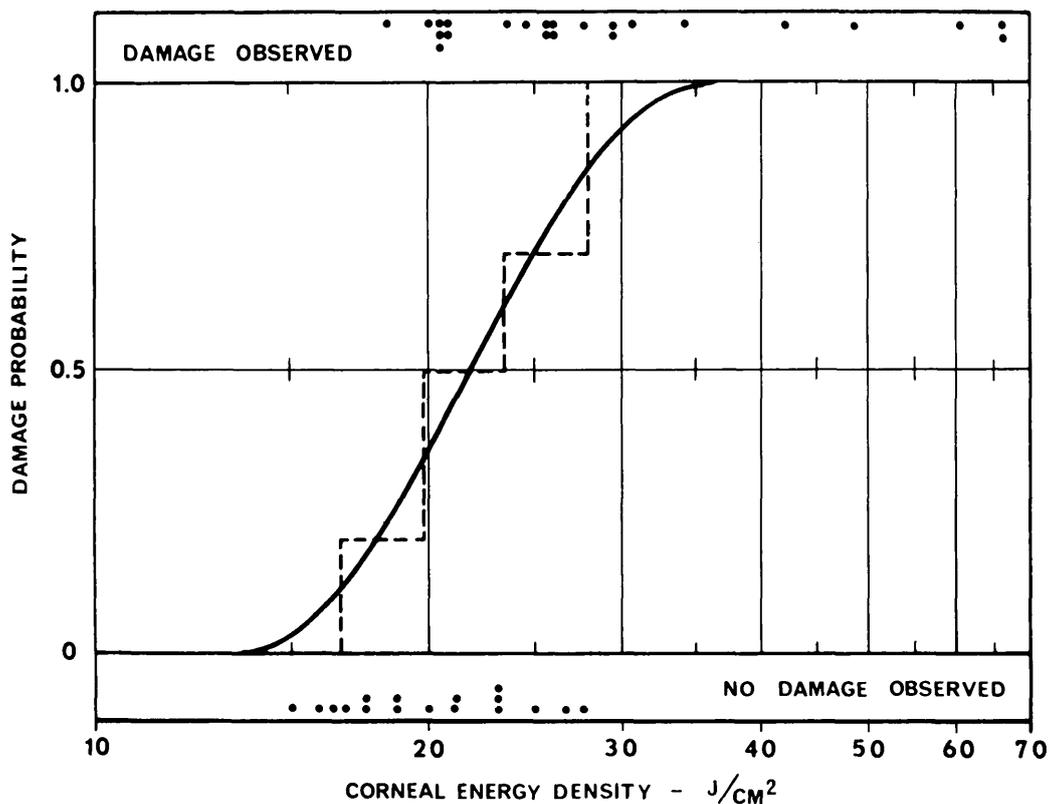


Fig. 7. Corneal damage probability plotted as a function of corneal energy density for Q-switched erbium laser. All exposures included were delivered in a single Q-switched pulse of 50 nanoseconds duration.

the anterior stroma (Fig. 6). No evidence of lenticular or retinal damage was found on careful examination of serial sections.

The probability of corneal damage as a function of incident corneal energy density is shown in Fig. 7. Each exposure in the focused-beam series was entered at its calculated energy density above or below the graph according to whether corneal damage was observed. A histogram was

constructed by dividing the energy density range into equal logarithmic intervals and computing the proportion of damage for each interval (the proportion of damage is equal to the number of exposures producing damage divided by the total number of exposures within the interval). A smooth curve was fitted to the histogram in order to approximate the probability curve for damage over the range of energy

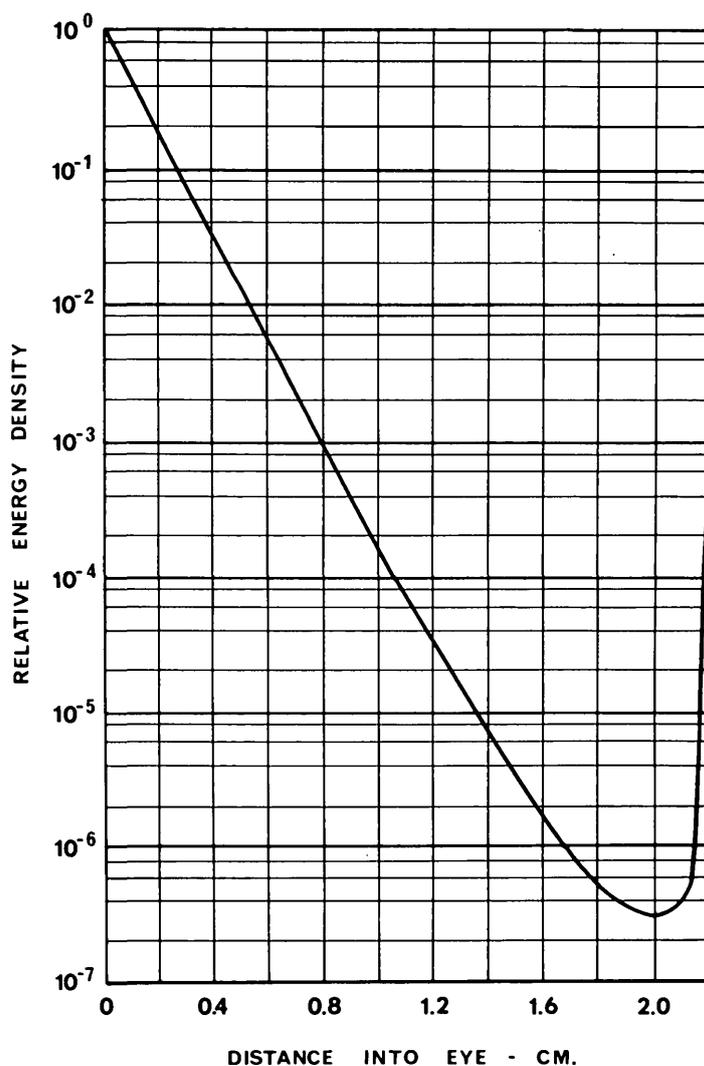


Fig. 8. Theoretical relative energy density distribution in the eye showing the combined effects of focusing and absorption of 1.54μ radiation. This "worst-case" analysis assumes a collimated beam with the eye refracted for infinity at 1.54μ , an 8 mm. pupil, a diffraction-limited retinal spot of 8μ in diameter and a 2.2 cm. axial length from the anterior corneal surface to the retina. The absorption coefficient of pure water is used (10 cm.^{-1}).

densities tested. The 0.5 damage probability obtained from the curve was 21 j./cm.². All exposures to energy densities greater than 30 j./cm.² produced injury, whereas no injury was detected below 17 j./cm.².

Discussion

This report represents the first published data on the ocular effects of the erbium laser. In order to produce any ocular injury with the erbium laser at energy outputs currently achievable, it was necessary to increase the energy density at the cornea by focusing the beam onto the cornea. Under these conditions observable ocular damage was restricted to the cornea. The use of a focused beam, however, does not result in the "worst case" situation for retinal damage; that is, a minimal retinal spot size produced by the eye from a collimated beam. When the direct collimated beam of the erbium laser was used, a corneal energy density of 1 j./cm.² did not produce any observable retinal damage. It is likely that even with much greater corneal energy densities no retinal damage would occur because of the attenuation through the eye at the erbium wavelength (Fig. 8). This is in sharp contrast to lasers operating in the visible and near-visible portions of the spectrum where the combined effects of high ocular transmission and focusing by the eye produce tremendous amplification of the incident energy density.³ In this respect the erbium laser represents a comparatively "safe" laser.

Corneal damage qualitatively similar to that produced by the Q-switched erbium laser has been described by several groups using the carbon-dioxide laser which operates in the infra-red at 10.6 μ .⁴⁻⁶ These

investigations have utilized a continuous-wave carbon dioxide laser and have included exposure durations down to the millisecond range. Before a precise quantitative comparison of carbon dioxide damage threshold values can be made with our data on erbium, experiments with a Q-switched CO₂ laser will have to be performed. Suffice it to say that, based upon the higher absorption coefficient of water at the 10.6 μ wavelength (950 cm.⁻¹) compared to the 1.54 μ wavelength (10 cm.⁻¹), one would expect a greater energy absorption per unit volume of irradiated corneal tissue and, thus, a lower corneal damage threshold for the Q-switched carbon dioxide laser.

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Space limitation

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