# Laser Safety and Accidental Laser Injuries to the Eye

T. Nishisaka

(Japan Advanced Institute of Science and Technology)

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T. Nishisaka
Japan Advanced Institute of Science and Technology
Tatsunokuchi, Ishikawa 923-12, Japan

With the widespread use of lasers, accidental ocular injuries occurred in many field. In order to decrease the incidence of laser accidents, it is essential to pay the attention for laser safety.

## 1. The Structure of the Eye(1)

The adult human eye is the size of approximately 25 mm in diameter. Figure 1 shows a simplified drawing of the human eye. Light passes through the various ocular structures to fall upon the retina where it triggers a photochemical process which evokes the neural impulses that lead to vision. The light first passes through the structures in the anterior portion of the eye -the cornea, the aqueous humor in the anterior chamber, the pupil, the lens, and into the posterior part and the vitreous humor and the numerous layers of the retina. Each eye is nearly a sphere and its movement is controlled by six muscles. The eye is protected from external blows by the brow ridge.

The cornea of the eye is living tissue which is exposed directly to the environmental elements. It is protected from drying out only by the tear film. The corneal epithelium has one of the highest metabolic rates in the entire body. The tear layer of 6 -10 um thickness which protects this cell layer and maintains wetness is fairly finely balanced. The aqueous is essentially water. The aqueous as well as the cornea serves as a heat-absorbing water filter for tile lens, protecting it from IR -B and IR -C thermal radiation. The pressure within the eye is determined by the balance between inflow and outflow. The iris is a normally heavily pigmented layer of muscular tissue which adjusts the pupil of the eye. Opposing radial and circular muscles adjust the size of the pupil from approximately 2 to 7 mm as a function of the average brightness of the subject being viewed. Myosis (pupil contraction) is most marked for rapid changes in retinal illumination. Gradual changes in ambient lighting has only a weak effect. The myosis is more pronounced if the central areas of the retina (fovea and macula) are illuminated than if peripheral areas are illuminated at the same level. The pupillary response is wave-length dependent in accord with adaptation of the retina. The organic pigments of the iris are similar to pigments in the skin and retina and do not strongly absorb in the near-infrared spectral band (IR-A). The lens is supported in place by fine ligaments which are connected to the ciliary body. The vitreous body, a colorless gel formed by collagen fibers with only a few cells, more or less fills the posterior chamber. The vitreous is attached both to the retina and to the ciliary body.

The retina is an extension of the brain and consists of several very complex layers of nerve cells. Figure 2 shows a schematic drawing of the retina emphasizing the nerves and their interconnections. There are two types of photoreceptor cells: rods and cones, names for the shape of the distal extension of the photoreceptor cell. In the retina there are probably 120 million rods averaging 60 um and 2 um in diameter and 6 million cones approximately 50 um long and 3 to 5 um in diameter. These receptor cells are interconnected by other specialized cells. The specific anatomical aspects of the retina of particular importance in a study of retinal injury from light sources are the retinal pigment epithelium (RPE) and adjacent layers. The outer segments of the rods and cones are immediately anterior to the RPE. The choroid is an extremely vascular spongy tissue with many pigment grant scattered throughout it. The thickness is variable; the average is about 250 um. The blood vessels are very large in the choroid, and even in the choriocapillaris where the smallest vessels are found, the capillaries are 10 to 30 um in diameter as compared to the 8 um or less of the normal capillaries. Only a single blood corpuscle can move at a time through a typical capillary in other parts of the body and then the corpuscles often must suffer considerable distortion in the process. The sclera is the dense, fibrous shell of the eye and is roughly spherical in shape. In the front of the eye it blends into the cornea, which might be considered as a transparent part of the sclera. The sclera is a little over 1 mm thick where the optic nerve enters and is approximately 0.5 mm at the equator or middle, and is again almost 1 mm thick in front where it blends into the cornea. The sclera is almost uniform in character, although the most superficial or outer portion has some blood vessels and the inner surface is laced with melanin particles. The shape of the eyeball is maintained by the rigidity of the sclera to some degree, but mostly by the internal pressure (about 10 mm Hg).

## 2. The Function of the Eye

The two-point discrimination is dependent on illumination and with high illuminance some subjects achieve 15 arc-seconds difference. Because of the neural processing that takes place in the retina and in the higher visual pathways, two adjacent lines can be distinguished to an even more refined degree of acuity. Vernier acuity exceeds two-point discrimination with the ability to detect a dislocation of 4 to 10 arc-seconds.

In a laser safety calculation, the physical properties of the retinal image are important. As the pupil size becomes larger, the retinal image would theoretically be expected to become smaller due to diffraction theory. However, reports of visual performance and actual measures of light images on the retina for various pupil sizes indicate that the blur circle on the retina actually gets larger. There is an important consequence of this increase in blur circle with increase in pupil diameter. When viewing a point source of light, such as a laser or a distant star, the retinal irradiance is greatly "amplified" over that at the cornea. That is, the "optical gain" of the eye (the ratio of the corneal-to-retinal irradiance) is of the order of 100,000 times. Rods play the major role in night vision and are responsible for the eye's ability to respond to very low light levels. A single flash of less than I 00 photons (perhaps only I 0) can be seen by the human eye. The peak wavelength of the visual response is approximately 500 nm for night vision.

### 2.1 Spectral Characteristics of the Ocular Media

The ocular media of the normal eye transmit at least 1% of the radiation over the entire range from 400 nm to 1400 nm. At wavelengths beyond 1400 nm, water absorbs very heavily, and essentially all incident radiation is absorbed very superficially, principally within the cornea. Figure 3 illustrates in a simplified fashion the optical transmission of the human eye and shows the fraction of light actually absorbed in the retina throughout this wavelength region. The spectral region between 400 to 1400 nm is often termed the retinal hazard region, but clearly the spectral characteristics of the ocular media play an important role in assessing optical hazards to the retina.

### 2.2 Dark Adaptation

Another remarkable characteristic of the retina is its ability to dark adapt. Figure 4 shows how the visual threshold changes as a function of time within the dark. A person placed in a darkened room suddenly will not at first be able to discern any objects in the room even if there is a small amount of light. After a time in the dark, various objects can be perceived. Sometimes this process takes as long as 20 to 30 minutes. Figure 4 illustrates the fact that the dark adaptation process goes through two periods-first an adaptation of the cones where the threshold of photopic vision gradually decreases and then reaches a plateau, and then the scotopic visual threshold rapidly decreases. Note that plots in Figure 4 have a logarithmic scale for threshold luminance. The straight lines in the log-log presentation show the exponential character of dark adaptation. The slope of the line is a function of the level of light adaptation.

## 3. Accidental laser Injuries to the eye in Japan

Figure 5 presents 28 cases of ocular injury from 1965 through 1995 involving all males, whose ages ranged from 20 to 43 y. Fourteen cases were damaged by Q-switched lasers at a wavelength of 1064 nm. Ocular hemorrhage occurred in 14 cases.

The hemorrhage occurred in exposed spots and the surrounding vessels. The Listed table showed the laser eye injuries occurred from 1976 to 1986. Of the 31 eyes injured, 19 were left eyes and 17 were right ones. Five types of lasers were involved in the accidents. Figure 6 showed pictures of intraocular hemorrhage of case 11 on the 3 day and one month after injuries.

When the accidents took place, most persons felt flashes suddenly in front of their eyes. Other persons experienced dazzle and photophobia for several hours after exposure. Changes in the ocular fundus included coagulation, edema or hemorrhage at the burned retinas during the early phase after injury.

**4. Shock wave generation and propagation in the eye[2)]**

Intraocular hemorrhages caused by accidental pulsed laser irradiation is not only observed on the laser-exposed site, but sometimes in the surrounding area of the retina as showed in figure 6. This suggests that there is another mechanism to destroy the eye vessels except a direct injury by exposure spot.

Many previous studies about the intraocular microsurgery using laser-disruption have investigated and discussed the generation and propagation behavior of the shock wave in the area surrounding a focused laser-irradiated site. Figure 7 shows distribution of shock waves on the sclera surface from the posterior pole to the equator after the irradiations. In the case of 532 nm laser pulse irradiation shown on the right side of figure 7, a shock wave with a high amplitude and frequency appeared immediately after the laser irradiation on the posterior pole (A on the figure). However, this high amplitude shock wave disappeared from about a 4 mm distance from the posterior pole (B on the figure). At about 42 us after the irradiation, high amplitude shock wave appeared again on the middle sclera surface between the pole and the equator (E, G on the figure). On the equator , the shock wave was detected at about 12us after the irradiation (H and I on the figure). In the case of 1064nm laser pulse irradiation, the distribution of shock waves on the sclera surface after the irradiation was almost the same as that in the case of 532 nm. However, the first shock wave detected on the 1064 nm laser-irradiated site (A on the figure) was consisted of lower frequency components than that on the 532 nm laser- irradiated site represented by A on the right side of figure 7.

It is known that the lights with 532 nm and 1064 nm of wavelength can reach the retinal surface because very little is absorbed at these wavelength. Therefore, main generation site of the shock waves induced by 532 nm and 1064 nm-pulsed laser pulses is in retina or posterior sclera. Figure 8 show constructed intraocular propagation stages of a laser-induced shock wave at 28.7u, 42.7u and 57.1 us after a pulsed laser irradiation, respectively. This figure simulates the shock wave propagation in the whole eye-ball after which the velocity of shock waves decays to the sound level around the irradiation site.

Drawn lines represent the shock fronts of direct shock wave from irradiated site, and first reflected shock waves. Each stage has nodes of first reflect shock waves shown by arrows in figure 8. Especially, stage B is similar to the distribution of shock waves on the line b in figure 7, i.e. a high amplitude shock wave appears on the middle sclera surface between the pole and the equator This constructive consideration suggested that this increasing of shock wave amplitude at such nodes cause the intraocular damages by a different mechanism from direct attack due to the initial shock wave around the laser irradiated site.

**Reference**


1) D.Sliney and M.Wolbarsht, Safety with Lasers and Other Optical Sources, A Comprehensive Handbook, Plenum Press, New York, pp 65-92

2) T.Nishisaka , S.Tanaka and Y. Miyamoto; Shock wave generation and propagation in the eye ball by pulsed laser irradiation in vitro, Proceeding of the Internat. Laser Cong. Lasers at the Dawn of the Third Millenium, in press

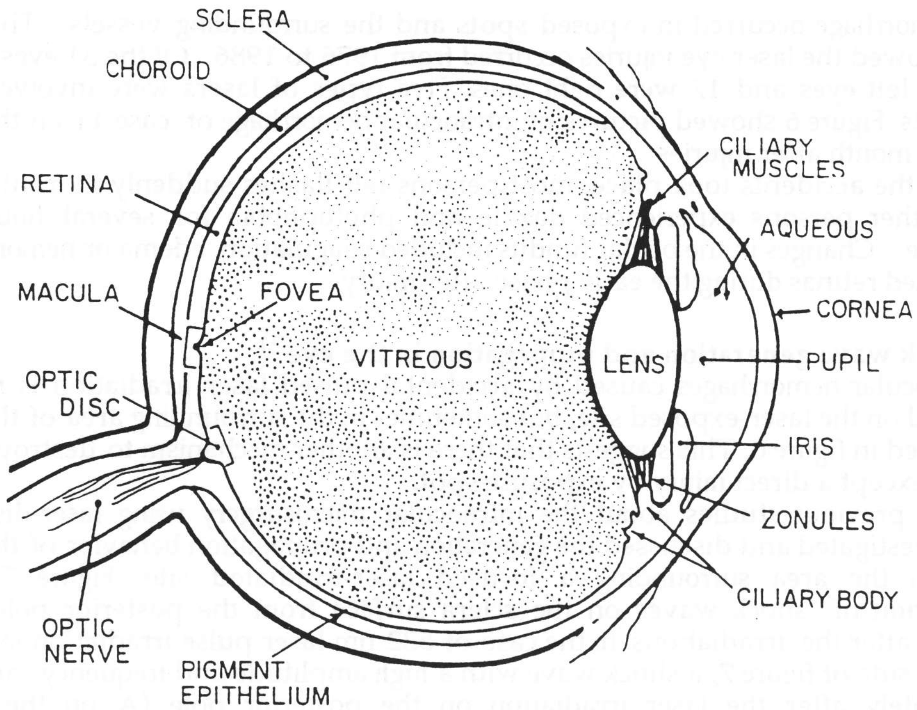



**Figure 1.** The general structure of the eye showing the principal structures referred to in this text. This cross-section is for a horizontal section as seen from above for a standard left eye.

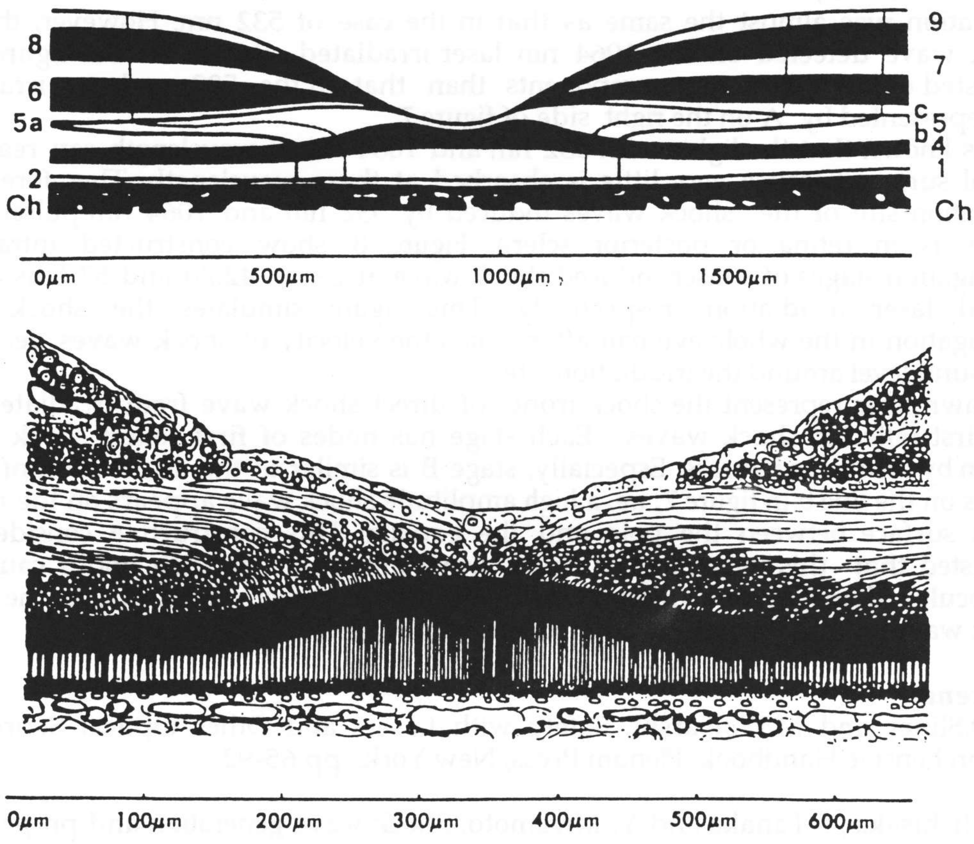



**Figure 2.** The Retina. This drawing of the layered structure of the retina illustrates the constriction of the neural layers near the fovea and their absence in the foveal pit (adapted from Polyak, 1941, *in* Adler, 1970, p. 425).

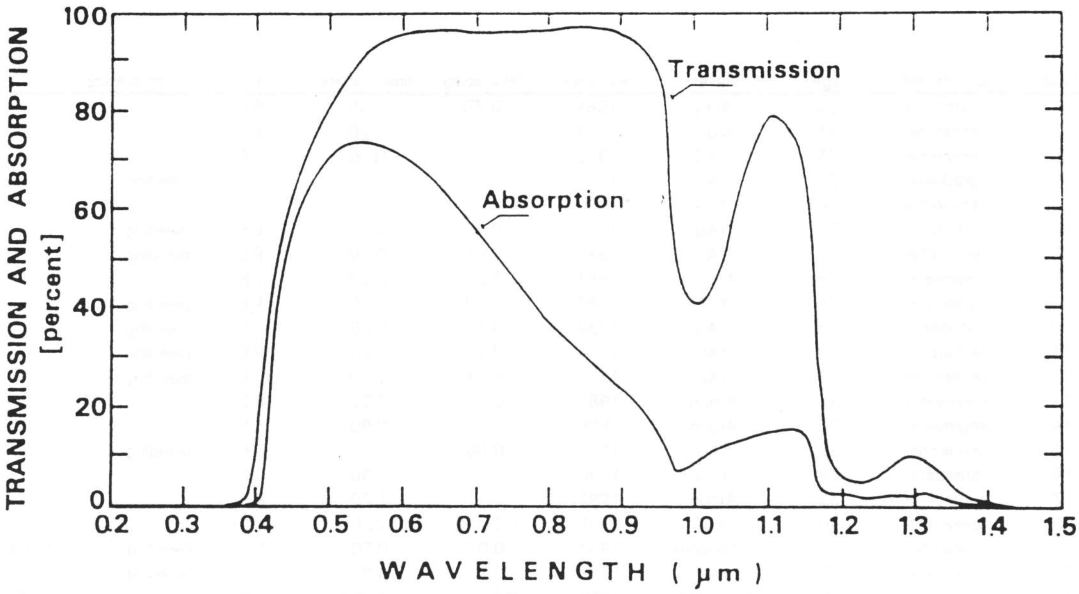



**Figure 3** Optical spectral transmission of the human eye and absorption of light energy in the retina and choroid as a function of equal corneal spectral irradiance. The upper curve of spectral transmission would be used in calculating a retinal irradiance. The lower curve would be used to calculate retinal absorbed dose rate (from the data of Geeraets and Berry, 1968).

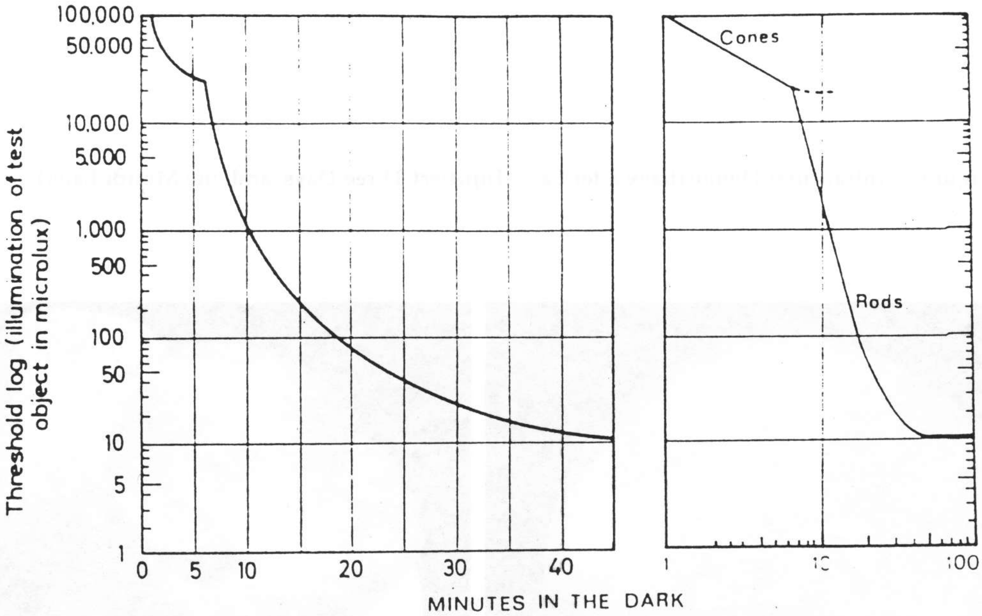
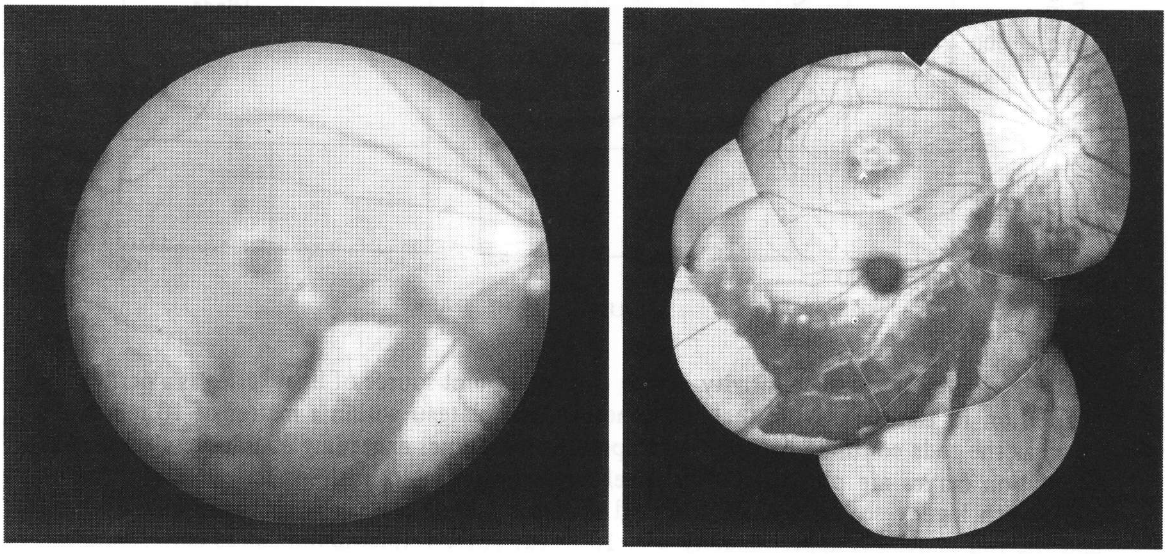



**Figure 4** The threshold sensitivity of the eye for a point source of light varies as a period of adaptation to the dark. Note that the cones reach a plateau within a matter of 10 minutes, whereas the rods continue to adapt up to periods sometimes exceeding 30 minutes. The dark-adaptation curves are plotted in two panels–one with semi-logarithmic scales (left) and the other with log-log scales. For an extended source the cone plateau is approximately 500 td and the rod plateau is approximately $5 \times 10^{-4}$ td. These retinal illuminances correspond to source luminances for an 8-mm pupil of 10 cd/m$^2$ and $10^{-5}$ cd/m$^2$ respectively. The unit of troland (td) is often used in these plots since it indicates the retinal illuminance and can be calculated easily from source luminance; i.e., the source luminance in cd/m$^2$ is multiplied by the pupillary area in mm$^2$ to obtain trolands.

| case | profession | age | laser | occurence | OH v. acuity | final v. acuity | site | reference |
|---|---|---|---|---|---|---|---|---|
| 1 | Instructor | 34 | Ruby | 1965 | 0.70 | 1.50 | R E | |
| 2 | researcher | 35 | Argon | 1973 | | 1.20 | L E | |
| 3 | researcher | 35 | YAG | 1975 | | 0.06 | L E | |
| 4 | graduate | 25 | YAG | 1979 | 0.08 | 1.20 | L E | bleeding |
| 5 | researcher | 30 | YAG | 1980 | | 0.80 | L E | |
| 6 | student | 23 | YAG | 1982 | 0.40 | 0.30 | L E | bleeding |
| 7 | researcher | 31 | YAG | 1982 | 0.01 | 0.10 | R E | bleeding |
| 8 | engineerer | 24 | Argon | 1983 | 0.20 | 0.20 | L E | |
| 9 | graduate | 26 | YAG | 1983 | 0.10 | 0.10 | L E | bleeding |
| 10 | student | 22 | YAG | 1984 | 0.10 | 0.60 | L E | bleeding |
| 11 | researcher | 23 | YAG | 1984 | 0.30 | 1.20 | R E | bleeding |
| 12 | researcher | 43 | YAG | 1987 | 0.04 | 0.10 | L E | bleeding |
| 13 | engineerer | 43 | Argon | 1988 | 0.90 | 0.90 | R E | |
| 14 | engineerer | 26 | Argon | 1988 | | 0.90 | L E | |
| 15 | researcher | 32 | YAG | 1989 | 0.06 | 1.20 | R E | bleeding |
| 16 | graduate | 24 | YAG | 1990 | | 1.50 | L E | |
| 17 | engineerer | 35 | Argon | 1991 | | 1.20 | R E | |
| 18 | researcher | 30 | YAG ? | 1991 | 0.5, 0.6 | 1.2, 1.0 | Both | |
| 19 | researcher | 30 | Ti-Sapphire | 1992 | 0.02 | 0.50 | L E | bleeding, IR-Card |
| 20 | graduate | 29 | YAG | 1992 | 0.70 | 0.90 | L E | bleeding |
| 21 | researcher | 20 | Excimer ? | 1992 | 0.5, 0.4 | 0.6, 0.9 | Both | 248nm |
| 22 | graduate | 24 | YAG | 1993 | 0.8 | 0.80 | L E | bleeding |
| 23 | researcher | 28 | YAG | 1993 | 0.10 | 0.20 | L E | bleeding |
| 24 | researcher | 38 | Ti-Sapphire | 1993 | 1.5 | 1.50 | L E | |
| 25 | student | 23 | YAG | 1994 | 0.08 | 0.40 | L E | bleeding |
| 26 | student | 23 | YAG | 1994 | 0.08 | 0.40 | L E | bleeding |
| 27 | researcher | 36 | Ti-Sapphire | 1995 | 0.04(1.2) | | R E | bleeding, femto sec. |
| 28 | researcher | 34 | YAG | 1995 | 0.5) | 0.8(0.9) | L E | bleeding |

**Figure 5** Accidental Laser Injuries to the Eye in Japan from 1965 through 1995

**Figure 6 Intraocular Hemorrhage after Laser Injuries( Three Days and one Month Later)**



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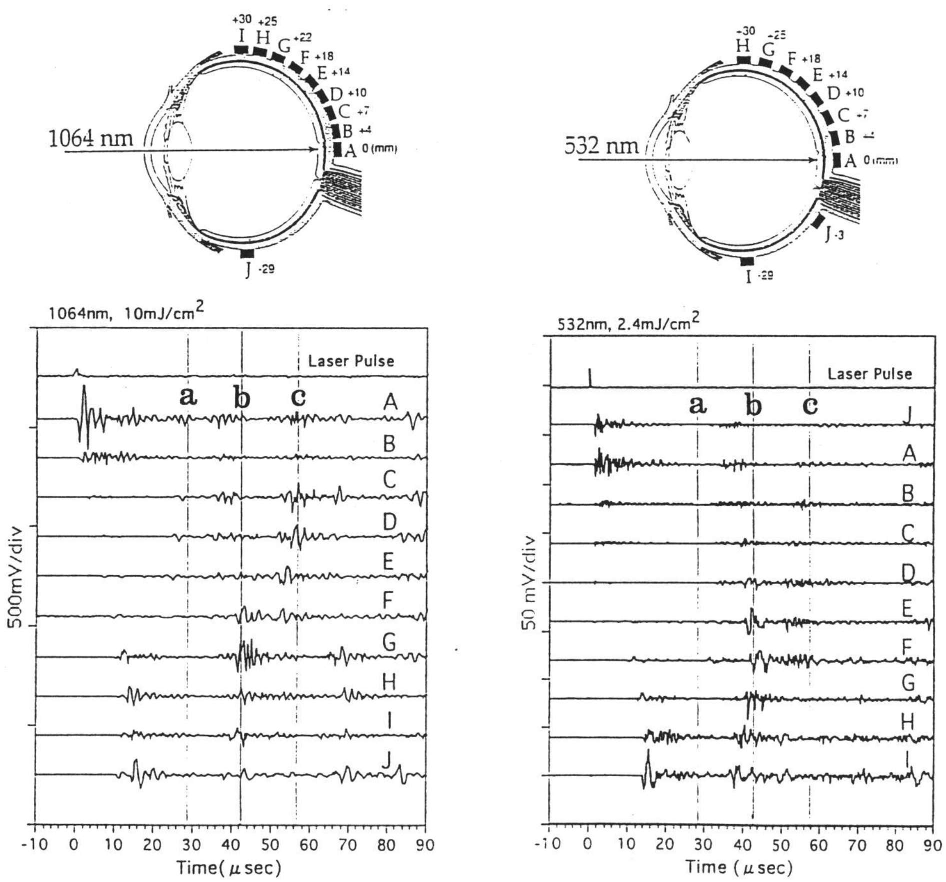
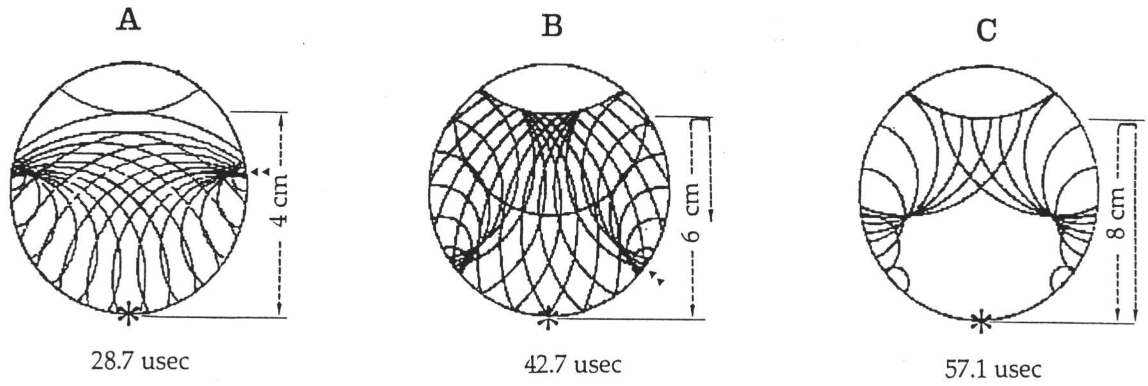



**Figure 7** Distributions of shock wave on the sclera surface from the posterior pole to the equator after the irradiations of 532 nm and 1064 nm pulsed laser beam. A represent the distances from the posterior pole corresponding to the laser-irradiated site.




Asterisk is indicating the initial point.
Parameters;
circle diameter : 50mm
vitreous velocity : 1400m/s

**Figure 8** Constructed intraocular propagation stages of a shock wave induce by pulsed laser beam. It is assumed that the diameter of the eye-ball is 5 cm, thickness of lens center parallel to the optical axis is 1 cm, and sound velocity of vitreous is 1400 m/s. Asterisk represents the generation site of the shock wave corresponding to the laser-irradiated site. Arrows show the nodes of shock waves. stage A, B and C correspond to the line a, b and c in figure 1, respectively.