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HAZARDS ASSOCIATED WITH CONTINUOUS LASER RADIATION

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Introduction

Immediate irreversible threshold injury level studies, suprathreshold studies and behavioral studies have been carried out with several types of lasers. These include investigation of effects on the eye, skin, joints and central nervous system. An outline of the various areas of investigation is presented below.

A. Ophthalmological Studies

1. Continuous laser radiation studies (1, 2, 3).
   a. Helium neon at 6328A
   b. Carbon dioxide at 10.6 microns

2. Pulsed laser radiation studies (4-8)
   a. Ruby at 6943A i. normal mode
      ii. Q-switched
   b. Neodymium at 1.06 microns-normal mode

B. Skin, Joints and Central Nervous System

1. Continuous laser radiation studies (9, 10)
   a. Carbon dioxide at 10.6 microns
   b. Argon lasers at ~ 5000A

2. Pulsed laser radiation studies (11-14)
   a. Ruby at 6943A i. normal mode
      ii. Q-switched
   b. Neodymium at 1.06 microns-normal mode

C. Behavioral Studies

1. Continuous laser radiation studies (15)
   a. Helium neon in the near infrared

2. Pulsed laser radiation studies (16)
   a. Ruby at 6943A

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Ophthalmological Studies

There are a number of reasons for the study of the interaction of laser radiation with the eye. These include investigations for both military and clinical purposes, as well as those oriented towards providing information relating to the physiology of vision and towards the design of laser systems for industrial applications. Studies relating to military and clinical situations can be categorized as follows.

A. Military

1. The development of ocular protection from:
   a. Accidental injury in the laboratory and in the field
   b. Deliberate injury in the field

2. The development of weapons to produce:
   a. Temporary blindness, such as dazzle or glare
   b. Permanent blindness, associated with burns or tissue destruction

Ocular burns or tissue destruction usually results in a scar which can produce interference with vision. The marked permanent degradation of vision which results can either occur immediately or not be evident until a period of time has elapsed. Delayed permanent blindness may be due to repeated insults which would not, individually, produce permanent damage. Studies on such cumulative effects are difficult to carry out, particularly since the time interval between the cause and effect may be long. This delayed blindness, or delayed degradation of vision, may be due to retinal injury, including injury to blood vessels, adjacent choroid and vitreous, or to injury to other ocular tissues such as the cornea or the lens. In this respect, both immediate and delayed permanent blindness can be due to similar causes - due either to injury to the retina or to injury to other than retinal tissues.

B. Clinical

1. The development of useful clinical instruments in ophthalmology.

With the advent of continuous lasers operating in various portions of the visible spectrum,

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such as the argon laser, it should be possible to design a photocoagulator with characteristics markedly superior to those presently available using xenon-arc systems. The superior characteristics would include controllable and variable pulse duration, peak power level, and spot size at the desired region of the eye. The relative monochromaticity of the radiation is a distinct advantage since narrow band optical filters can be used to attenuate the reflected laser radiation during concurrent viewing of the irradiation site. The potentially smaller physical size of the light source and the greater flexibility of the delivery system of the gas laser is an advantage over current xenon-arc coagulators. Lower instrument costs are also to be expected.

2. Ocular protection from accidental injury.

The requirements for protection in a clinical setting differ from that in a military setting. Clinical pulsed instruments are low energy devices (a few joules at most) in contrast to military units which can operate at much higher energy levels. The same is true for continuous or high p.r.f. systems insofar as power is concerned. A clinical unit is used in a controlled environment with potential hazard to few personnel in contrast to military systems which may be used in the field in an uncontrolled environment with potential hazard to many personnel, friendly, neutral and unfriendly. Also, for therapeutic purposes, the laser system is used under conditions in which there is existing disease in the eye, or ocular problems which require the use of a coagulator. This is in contradistinction to the use of lasers in field operations.

3. Functional studies using attenuated laser beams.

The relatively high intensity and monochromaticity, together with the small achievable spot size, may permit information to be obtained pertinent to an understanding of retinal (or visual) function. Data of this type may assist in elucidating the processes relating to temporary blindness.

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General Considerations for Ocular Injury

From the point of view of the eye, there is no question that injury can be produced if sufficient energy is absorbed within a given volume of ocular tissue in a specific period of time, under both military and clinical environmental conditions. The primary ocular target region can be defined as that region of the eye in which the energy absorption per unit volume of ocular tissue is greatest when the beam is directed along the optic axis of the eye and is of greater diameter than the eye(Fig. 1). The location of this region is dependent primarily on the wavelength of the radiation. Insofar as hazards are concerned, it is this primary target region which forms the basis for the determination of immediate irreversible threshold injury. Although the various ocular media may vary in their sensitivity to thermal injury, it is probable that for immediate irreversible injury, the sensitivity to thermal injury of the various media can be considered as grossly equivalent within an order of magnitude. That is, to a first approximation, the same amount of energy must be absorbed in a given volume of ocular tissue under the specific irradiation conditions to produce irreversible injury. This may be modified somewhat by differences in tissue environment and geometry. For example, the cornea is bounded by a free surface whereas the retina is contained within a fairly rigid, closed, filled cavity. It should also be understood that the above places no value on the importance of the injury - it does not imply that a lesion of the iris or of the peripheral retina will, for example, be equal in importance to one of the macula.

Under some conditions, such as with the beam at right angles to the optic axis, the primary ocular target region would not be the area injured. For example, under the above conditions, for pulsed ruby or neodymium lasers, the region of injury would be the cornea, sclera or lens rather than the retina. It is probable, however, that injury under

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these conditions will always require higher incident levels than for injury to the primary ocular target region. Although these secondary ocular target regions have, in general, been neglected in evaluations of threshold injury, some thought has recently been given to effects produced by other than beams directed along the optic axis (17, 18).

The remainder of this paper will be devoted to a discussion of some of the hazards associated with CW radiation from He-Ne and CO_2 lasers.

A. Helium-Neon Studies

For the normal eye the primary ocular target at 6328A is the chorio-retinal region. This is based on the high percent transmission of the ocular media anterior to the retina at this wavelength. The focusing properties of the eye does not in itself determine the primary ocular target since the radiation can be focused in the vitreous. However, since the absorption coefficient of the vitreous is less than that of the chorio-retinal region, the primary target site and consequently the gross injury threshold region at a specific input power will occur in the retinal-choroidal region.

Experimental studies at 6328A have been reported by Kohtiao, et al (1, 2). Lesions were produced in retinas of chinchilla rabbits on 2.5 second exposure to a 25 milliwatt multimode He-Ne laser. The retinal image size was 0.25 mm; the retinal power density was therefore of the order of 40 watts/cm^2, assuming most of the incident radiation reached the retina. A temperature rise of 7.8 ^{o}C was recorded in the lesion, with a rapid decrement in temperature elevation laterally. Increasing the exposure time to as long as 30 minutes did not apparently increase the intensity of the lesion; data on exposure time shorter than 2.5 seconds at this power level was not given. No lesions were observed following irradiation at a power level of 2 milliwatts for 1 hour and at a power level of 5 milliwatts. In other experimental studies, a retinal temperature elevation of 12 ^{o}C to 20 ^{o}C was produced for a 1.2mm diameter threshold lesion on exposure to intense visible light (23).

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The above experimental data does not include injury thresholds for the very small retinal image diameters which can be encountered with highly collimated lasers, and which would represent a "worst case" situation. Direct temperature measurements for very small retinal image diameters is difficult. For example, if a thermocouple is used, its thermal characteristics, physical size and inaccuracy in placement would result in considerable error in temperature measurement. Therefore, to assess the hazards from highly collimated lasers, one must calculate the maximum retinal temperature elevation utilizing suitable models for heat conduction in retinal tissue.

A calculation of the retinal temperature elevation under "worst case" viewing conditions is carried out below, and the results compared with experimental data. The "worst case" viewing conditions include the following factors: the retinal image diameter is the minimum diameter achievable (10 microns (24)); the distribution of laser power density is uniform across the retinal image; steady-state flow conditions are reached. In order to develop an adequate threshold injury model, both the absorption of radiation in the various ocular media and the allowable temperature elevation at the site of injury must also be known. Measurements, performed by several groups indicate that at 6328A, light suffers only a small reflection loss at the anterior surface of the cornea, and then passes virtually unattenuated through the cornea, aqueous, lens, and vitreous (25, 26). However, based on in vitro data, from 15% to 40% of the incident radiation at this wavelength is absorbed in a thin layer of retinal pigment epithelium, the region at which maximal absorption of energy per unit volume occurs at this wavelength(25, 27). Sufficient energy absorption in the pigment epithelium can elevate the temperature in this region to a level where an ophthalmoscopically visible retinal lesion is produced. In order to quantitatively assess laser hazards, a safe human retinal temperature elevation must be assumed. Based on the experimental temperature values given above

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and an estimate of the body temperature elevation encountered in fever, it can be assumed that a human retinal temperature elevation of 2° C can be considered safe over a protracted time.

The following mathematical model can therefore be used to compute the temperature elevation in the human retinal pigment epithelium. Consider a cylindrical volume of retinal pigment epithelium in which laser radiation is absorbed and in which heat is uniformly generated. The maximum transient temperature elevation, U_{τ}, occurs at the center of the irradiated volume of pigment epithelium at the end of the radiant pulse of time duration τ. This temperature rise is given by (19):

$$U_{\tau} = \frac{AP_R}{2\ell\rho c} \int_0^{t=\tau} 1 - e^{-a^2/4Dt} \quad \mathrm{erf} \frac{\ell}{\sqrt{4Dt}} \, dt \qquad (1)$$

where P_R = retinal power density (cal/sec/cm^2), A is the fraction of the retinal power density absorbed by the pigment epithelium, $2\ell = 10^{-3}$ cm, the thickness of pigment epithelium (28), ρc = volumetric heat capacity of pigment epithelium ($\approx$ 1 cal/cm^3 / ^{o}C), a = retinal image radius (cm), D = thermal diffusivity ($\approx 1.76 \times 10^{-3}$ c.g.s.), and τ = pulse duration in seconds.

The maximum steady-state temperature rise, U_{ss}, is obtained by solving the steady state heat flow equation:

$$U_{ss} = \frac{AP_R}{8K} \left[2\sqrt{\ell^2 + a^2} + \frac{a^2}{\ell} \log \frac{\sqrt{\ell^2 + a^2} + \ell}{\sqrt{\ell^2 + a^2} - \ell} \right] \qquad (2)$$

In equation 2, K = thermal conductivity which is assumed to be that of water ($\approx 1.76 \times 10^{-3}$ c.g.s.).

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For constant power P_L, entering the eye, U_{ss} decreases as the retinal image radius is increased. Substituting $P_L = \pi a^2 P_R$ and assuming $a >> \ell$ in equation 2, the following expression is obtained:

$$U_{ss} = \frac{AP_L}{2 \pi a K} \tag{3}$$

From equation 2, the minimum achievable retinal image diameter ($2a = 10 \mu$) will result in the highest temperature elevation. In this "worst case" analysis, temperature contributions from absorption of radiation by the choroid is neglected. This is based on the much smaller absorption coefficient for the choroid. The validity of equation 3 can be determined by a comparison with temperature measurements in the rabbit retina performed during He-Ne laser photocoagulation studies reported by Kohtiao, et al., as outlined above. The retinal temperature rise at the center of the threshold lesion was measured with fine thermocouples and reported to be 7.8° C by Kohtiao, et al. If the above irradiation and absorption data is used in conjunction with equation 3 of this communication ($a >> \ell$), U_{ss} is calculated to be 17 °C when 40% of the incident radiation is assumed to be absorbed in the rabbit retinal pigment epithelium. If 15% absorption is assumed for the rabbit retinal pigment epithelium then U_{ss} is calculated to be 6 °C. Therefore, for the range of percent absorption that has been reported for the pigmented rabbit retina, there is good agreement between the theoretical values of temperature rise obtained from the analysis presented in this communication and the experimental values reported by Kohtiao, et al., for a threshold lesion produced in a retinal image diameter of 0.25 mm.

In the above equations it should be noted that a factor of 2.5 increase in temperature will be obtained if the percent absorption A, is 100% rather than 40%.

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If a safety factor is to be considered, it may be necessary, on a "worst case" basis to utilize this higher absorption value.

For the case of the 10 micron retinal image diameter, equation 2 must be employed to calculate the maximum safe total laser power entering the eye. To obtain this value, the following conditions are assumed for a "worst case" analysis: A = 100%; retinal image diameter is 10 microns; allowable temperature rise is 2° C; and choroidal energy absorption and heat dissipation due to blood flow are neglected. From equation 2, the maximum safe total laser power at 6328A entering the pupillary aperture is then calculated to be of the order of 50 microwatts. It is probable, however, that A = 40% is a more realistic estimate for a worst case situation. On this basis the maximum safe total laser power at 6328A entering the pupil is calculated to be of the order of 100 microwatts. This would then obviously be a safe peak power level for pulsed operation as well. This maximum safe total laser power entering the eye for other lasers in the visible spectrum, such as the argon laser, should also be of the same order of magnitude. This value should be contrasted with the power entering the pupil on direct viewing of the sun, which is of the order of 100 milliwatts for a widely dilated pupil and is distinctly hazardous.

In order to specify safety standards, an arbitrary "safety factor" must be introduced. This has not been included in the above calculations for the He-Ne laser.

A study by Vasilenko, Chobetaev and Troitskii (15) demonstrated that "high energy" gas lasers (λ = 1110-1180 mμ) aimed at the human eye induced color sensations typically produced only by visible wavelengths between 560 (yellow-green) and 600 (yellow-orange) mμ . This observation resulted from having eight to ten subjects match laser induced sensations with those induced by visible light from a prism. The authors concluded that frequency doubling may have occurred resulting in the above visual sensations. Power levels were not given, however. Although the laser was not specified, it was probably a

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He-Ne unit.

B. Carbon Dioxide Laser Studies

The primary ocular target at 10.6 microns is the cornea. This is predicated on the relative exposure of the cornea to the radiation as compared to that of the adjoining sclera which is protected to a greater extent by the lids, and the high absorption coefficient of biological tissue ($> 150\ cm^{-1}$) at this wavelength, which results in high absorption in the superficial layers. Injury to other than the superficial epithelial layers of the cornea and the underlying Bowmans' membrane (in human eye) will result in healing by scar formation. Such a scar occurring in the visual axis of the eye (pupillary area of the cornea) can be expected to interfere with useful vision. Since prevention of such scarring, upon healing is generally impossible with medical treatment alone, restoration of useful vision will then depend on subsequent removal of the scarred cornea and its replacement with normal corneal tissue obtained from a donor eye (i.e., corneal transplantation).

CO_2 laser radiation studies have consequently been oriented towards three aspects:

1. Determination of power density levels required to produce threshold lesions.

   a. Clinical, gross and microscopic studies
   b. Production of aberrant corneal epithelial cells

2. Determination of injury and repair on suprathreshold irradiation.

3. Studies on protective devices.

I. Threshold Studies

a) Clinical, gross and microscopic studies.

As the power density of the incident radiation is decreased, the time required to produce a threshold lesion is increased. In order to obtain statistically significant data, a considerable number of animals would be required to obtain power density -

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exposure time threshold data. Since biological tissues have high and probably similar absorption coefficients at this wavelength (experimental absorption coefficients, α, ranged between 130 cm^{-1} and 270 cm^{-1}) (Fig. 2), threshold studies at short pulse durations were carried out on rodent skin. This permitted a number of studies to be carried out on each small rodent at minimal cost. The data obtained on threshold lesions at various power densities (Fig. 3) was fitted to one-dimensional heat flow equations under the following assumptions.

If the irradiated skin and underlying tissue is assumed to be a uniform, semi-infinite medium with absorption coefficient, α cm^{-1}, then the following equation for one-dimensional heat flow holds for the maximum surface temperature rise, Δ T, at the center of the irradiated spot.

$$\Delta T = \frac{(1-R)h}{4.18} \quad \frac{1.13\sqrt{\tau}}{K\rho c} - \frac{1 - \exp(\alpha^2 D\tau)\cdot \mathrm{erfc}(\alpha\sqrt{D\tau})}{\alpha K} \qquad (4)$$

In using equation 4 for the analysis of threshold lesions, the value of $\sqrt{K\rho c}$ was chosen as 0.042 c.g.s. units, based on measurements of the thermal conductivity $K = 1.76 \times 10^{-3}$ c.g.s. units and the volumetric heat capacity, $\rho c \simeq 1$ cal/cm^3/^oC by Davies (20). The incident irradiance, h, is measured in watts/cm^2 ; the exposure time, τ, in seconds. The thermal diffusivity is given by $D = \frac{K}{\rho c}$. The reflectivity, $R < 5\%$, is based on observations by Hardy (21) and on in vivo and spectrographic measurements of reflectance.

In calculating a maximum surface temperature, errors resulting from radial heat flow during the pulse are less than 10 percent at the beam center if the square of the beam radius, a, is greater than 4 $D\tau$. In these experimental investigations, the ratio $4 D\tau/a^2$ was approximately 0.14. Consequently, radial heat flow is negligible near the

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beam center during the radiant pulse, and one-dimensional heat flow can be considered to apply in this region.

The absorption coefficients for tissues are high in the wavelength region about 10 microns. Some of these data are summarized in Figure 2 and compared to measured absorption in several rat tissues. Since the absorption coefficients at 10.6 microns (Fig. 2) range from 130 cm^{-1} to 270 cm^{-1}, radiation at this wavelength is attenuated in tissue by 60 percent at depths ranging from 37 to 77 microns. A reasonable approximation for a heat flow analysis, is therefore, one in which the tissue is considered as completely opaque. Consequently, in the limit as $\alpha \rightarrow \infty$ equation 4 reduces to the following form:

$$\Delta T = \frac{(1 - R)h\sqrt{\tau}}{3.70\sqrt{K\rho c}} \qquad (5)$$

Based on thermal constants given above, equation 5 predicts a maximum surface temperature rise at the lesion center of 22 °C ± 15 percent for the thresholds shown in Figure 1. Actual temperature measurements utilizing a thermocouple injected following the pulse, were 22 °C ± 20 percent. A constant temperature curve (isotherm) is drawn in Figure 3 representing the probability of inducing a gross, immediate lesion in almost all cases. This isotherm is in excellent agreement with the experimental data. Values of h and τ to the right of this isotherm should result in an immediate lesion approaching 100 percent probability. The total energy density required to produce threshold lesions consequently decreases with decreasing exposure time as shown from this data (Fig. 4).

To establish a power level below which injury would not be produced on long duration irradiation, irradiations of the eyes of rabbits were carried out in vivo at 0.5, 0.3, 0.2, and 0.1 watts/cm^2 for 30 min. At 0.5 watts/cm^2, corneal lesions were produced in less than 5 minutes. At 0.3 watts/cm^2, lesions consisting of abrasion of the anterior corneal surface and opacification within the cornea, probably due to protein

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coagulation, was evident (Fig. 5). At 0.2 watts/cm^2, variable abrasion of the epithelial layers of cornea and corneal opacification was observed (Fig. 6). At 0.1 watts/cm^2, no gross (i.e., clinical) abnormalities of the cornea could be seen.

In order to substantiate the above values for threshold injury of the eye, on prolonged exposure, irradiation of the forefinger was carried out by the senior author. At 0.3 watts/cm^2, the irradiation resulted in considerable, but bearable pain. The irradiated region was more sensitive, slightly erythematous and swollen over the next several days. At 0.1watts/cm^2, there was little evident increase in temperature at the irradiation site. There was also no pain or discomfort. Consequently, it is probable that 0.1 watts/cm^2 is a reasonable estimate for gross threshold injury to the rabbit eye at 10.6 microns. Although there is some difference in the histology of the cornea between rabbit and man, it is probable that the threshold data obtained, 0.1 watts/cm^2, on rabbit corneas is, in general, valid for man.

There are however, some factors which must be considered in arriving at the above estimates. The power measurements were made using an Eppley thermopile, with suitable aperturing. Although the laser was operated in a multimode pattern, an attempt was made to select a uniform portion of the beam. Since these were long duration irradiations, the effect of any spatial nonuniformity in the beam pattern would be expected to be integrated out. Although rapid variation in beam pattern is not detectable with the Eppley (time constant 0.25 seconds), the long-term stability of the output was determined to be within 10% for one-half hour.

Based on the above, the threshold power density for corneal threshold injury is estimated to be 0.1 watts/cm^2.

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b) Production of aberrant corneal epithelial cells following laser irradiation.

At the U. S. Army Medical Research Laboratory, it has been recently shown by Parr and Fisher that cells of the corneal epithelium of rats are significantly altered after exposure to laser radiation (22). This effect was first demonstrated and studied using the ruby laser and appears to be dose dependent (Figs. 7, 8). While the exact origin of these abnormal cells is not clearly evident, present indications are that cells in active mitosis are preferentially affected. The significance of the effect may represent a long-term hazard, since studies just completed show that atypical cells persist for one year, while the life span of the normal cell (resting stage-dividing stage) is generally considered to be between 5 and 10 days.

Studies by Parr, Peacodk and Fisher indicate that the threshold range for the production of these atypical cells at 6943A lies between 0.25 j/cm^2 and 1.0 j/cm^2 incident radiation dose for a 3 millisecond pulse. This effect does not appear to be an important hazard since the levels are higher than the exposure necessary to produce retinal damage. However, with CO_2 laser radiation a similar effect has been demonstrated in individual animals. This effect may represent a significant hazard since 10.6 micron radiation is totally absorbed by the cornea. Preliminary data indicate that the threshold dose for this effect for 0.1 second exposure time may be of the order of 7.0 watts/cm^2. Studies in this case suggest also that the production of aberrant cells is dependent on tissue temperature change.

The exposure levels at which atypical cell production with CO_2 laser occurs appear to be below the levels causing any immediate grossly visible damage to the cornea. These atypical cells are observed only by using special histological techniques, which include removal of the cornea from the eye, staining, and mounting intact for examination

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of individual cells under oil immersion.

Present studies with this effect are being conducted to determine CO_2 laser thresholds more accurately and over wider ranges of exposure conditions. A mathematical model is being developed in order to predict injury and thresholds and to describe the extent of injury.

II. Studies on Injury and Repair Following Suprathreshold Irradiation of the Eye.

For suprathreshold studies, rabbit eyes were exposed in vivo to CO_2 radiation at incident power levels from 3 to 20 watts. The exposure time was held constant at 1 second, the spot diameter at 5 mm. The various ocular changes that occurred were evaluated clinically, grossly, and histopathologically using both light and electron microscopy.

At a power level of 3 watts (15 watts/cm^2) a dense white corneal opacity was produced (Fig. 9). With increase in power density, deeper penetration into the corneal stroma was produced in the form of an ulcer-like crater. This was associated with corneal thickening consisting of both "fused" and "nonfused" lamellae. Some of the lesions that did not penetrate into the eye were accompanied by a depression of the anterior lens surface (Fig. 10) due to either heat transmission or to increased pressure on the anterior lens surface. This effect on the lens must be considered in ophthalmologic management of laser injury at this wavelength. Deeper intraocular changes were not observed in the non-penetrated eye within the limited time interval between irradiation and these observations. However, since there is an alteration in the shape of the lens, deeper intraocular changes cannot be excluded. At power levels in excess of 10 watts (50 watts/cm^2) penetration into the anterior chamber along with ejection of a stream of aqueous occurred.

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On histological examination of the cornea, the artifactious clefting or lamellar stromal separation usually observed was replaced by a "fusion" of the corneal lamellae at the periphery of the lesion. This region lost affinity for Masson trichrome and Van Gieson stains, affinity for which is characteristic for collagen. This suggestion that the collagen in this region might be chemically altered was further supported by electron microscopic observations of areas of increased density along the collagen fibrils in the region of the fused lamellae, presumably foci of heat denaturation. These foci may in part be the reason for the unusually firm "fusion" or adherence of the stromal lamellae in this region.

III. Studies on CO_2 Eye Protective Materials

Eye protective devices, which have not been specifically designed for protection against CO_2 laser radiation are used by many investigators. These include cellulose acetate goggles and face masks and welders' goggles and masks with clear or tinted glass. In some cases, reliance is placed on normal corrective glasses in standard frames for protection. To determine their limitations for protection on CO_2 irradiation, the properties of these devices were examined.

Based on experimental studies, the following factors appear to be of significance: Corrective glasses have metal rims or hinges which reflect the radiation. They do not protect more than the eye area, do not offer protection at all angles of incidence and may fog. Face masks usually protect the face and often the front of the scalp, but sometimes have metal exposed to the beam, are usually awkward and impede both communication and peripheral vision. Cellulose acetate goggles do not protect the hair and lower face, usually impede vision and may be uncomfortable. Welders' goggles and masks may have heavily tinted glass inserts which impede vision. The goggles protect

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only the eye area; the masks are usually awkward, uncomfortable, impede communication, and have large opaque areas which reduce the visual field.

On CO_2 irradiation studies of cellulose acetate, slow "ablation" of the surface was produced at power densities below 10 watts/cm^2, in which the "ablation" would not necessarily be noticed unless the irradiation site were in direct view. Consequently, at low power densities, irradiation of a protective cellulose acetate shield might not be noticed until after protection failed.

Based on CO_2 irradiation studies on glass, it appeared that for protective purposes, the dimensions of the glass inserts should be large in comparison with the dimensions of the beam. This assumes that the inserts would be set in a frame which prevents overall irradiation of the insert.

The production of permanent stresses in glass which had been heated to the annealing range on CO_2 irradiation resulted in rapid fracture on re-exposure. Consequently, polariscopes or similar devices should be considered for examination of permanent stress patterns in protective goggles or masks.

When clear glass was irradiated with a focused CO_2 beam, operating in the 10 watt range, an intense white light, painful to observe and possibly leading to "flash blindness" was produced. If the light is intense and over a large region of the protective surface, high retinal irradiance resulting in reversible blindness or even irreversible injury could result. When shade #6 glass was irradiated, only a dull red glow was observed. Since unnecessary tinting of the glass may interfere with vision, it is probable that an adaptive filter type of material should be considered in the design of eye protective devices.

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SUMMARY

Ocular hazards associated with cw gas lasers have been discussed. Retinal lesions have been produced by irradiation at 25 milliwatts at 6328A. Calculations indicate that 100 microwatts entering the pupil is an order of magnitude estimate of "worst case" threshold power levels. Possible frequency doubling on irradiation at 1110-1180 mμ has been reported.

CO_2 laser thresholds are of the order of 0.1 watts/cm^2. The production of aberrant corneal cells of the rat on CO_2 irradiation has been observed.

Injury to the eye on CO_2 irradiation will result in corneal scarring which will interfere with vision. Injury to tissues deep to the cornea such as to the lens may be produced without corneal perforation on CO_2 irradiation.

Consideration must be given to protection of hair and skin as well as to the eyes for minimization of hazards in a 10.6 micron irradiation field.

The production of a permanent stress in eye protective devices on exposure should be avoided since this may result in explosive fracture on re-exposure.

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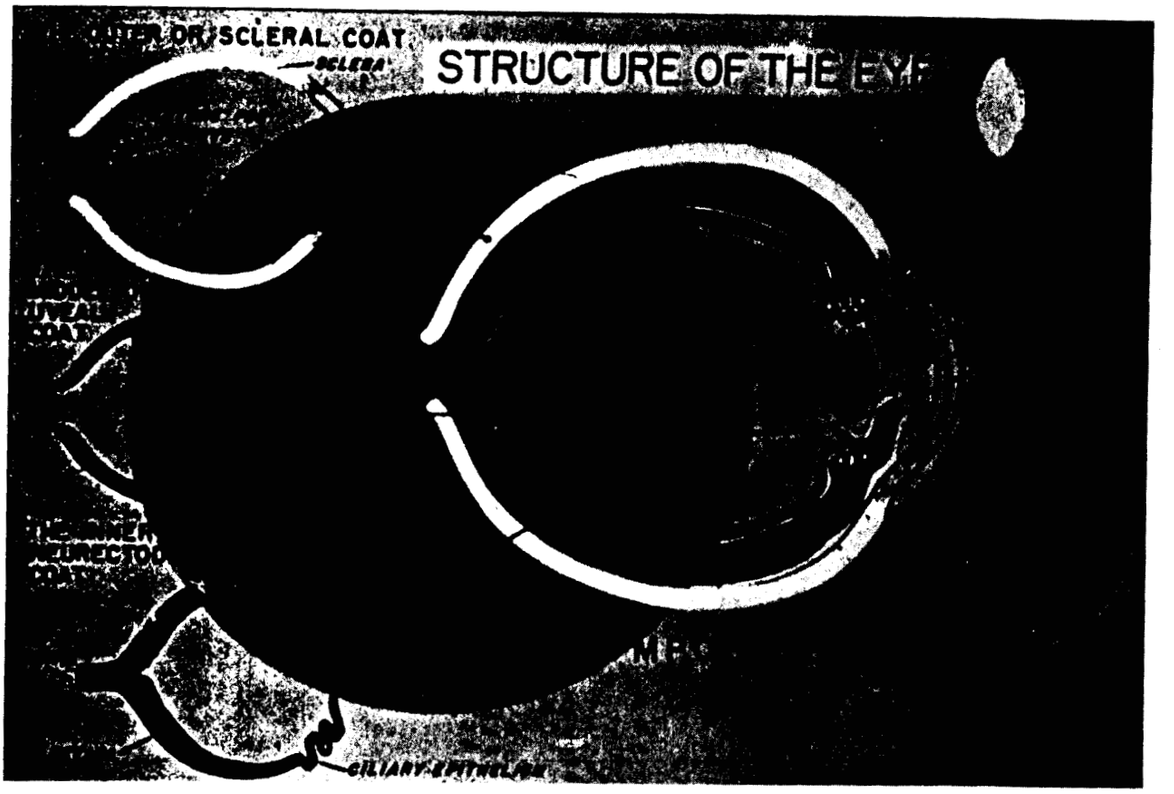
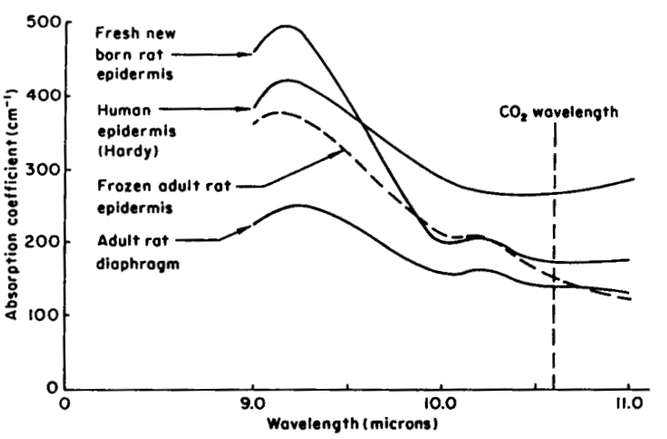


Fig. 1 Structure of the eye

Fig. 2 Absorption coefficients for in vitro biological tissues.



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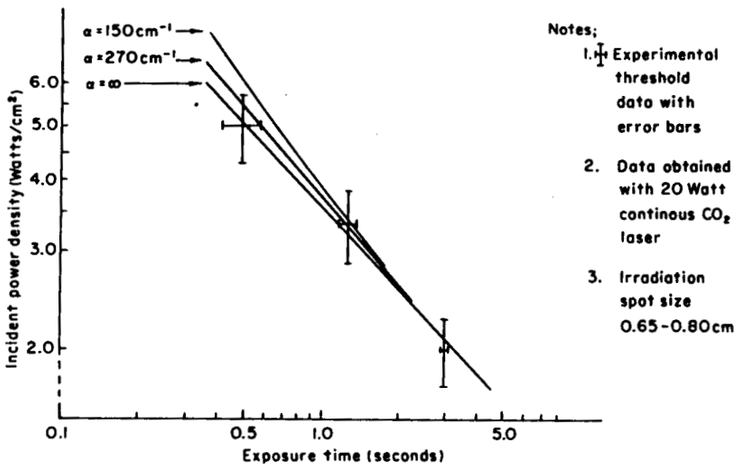

Fig. 3 Isotherms for approximately 100% frequency for visible threshold lesion of rodent skin calculated from opaque and non-opaque thermal models (log-log plot).

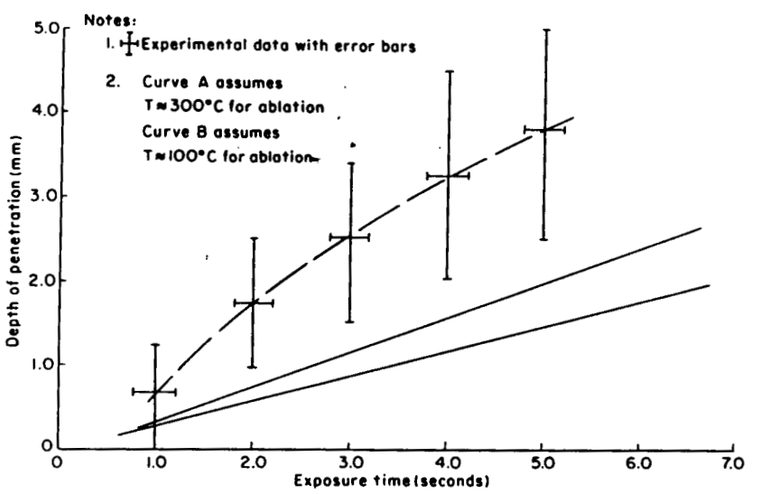

Fig. 4 Energy density for approximately 100% lesion frequency threshold for rodent skin. Experimental data compared to curve calculated from opaque thermal model.

Fig. 5 Opacification within the rabbit cornea following CO_2 laser irradiation at 0.3 watts/cm^2 for 30 minutes. Photograph 1 day post-irradiation.

Fig. 6 Variable abrasion of epithelial layers of cornea and corneal opacification following CO_2 laser irradiation at 0.2 watts/cm^2 for 30 minutes. Photograph 1 day post-irradiation.

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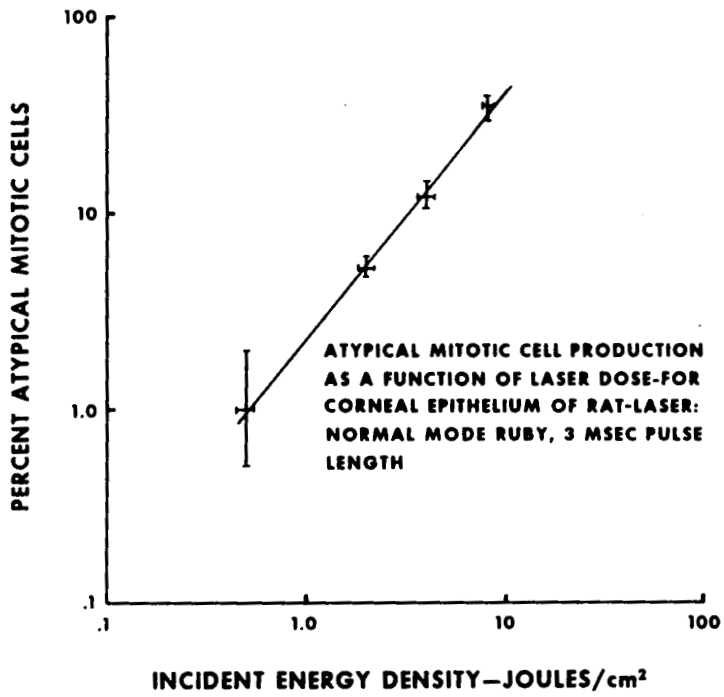

Fig. 7 Percent atypical mitotic cells as a function of incident energy density.

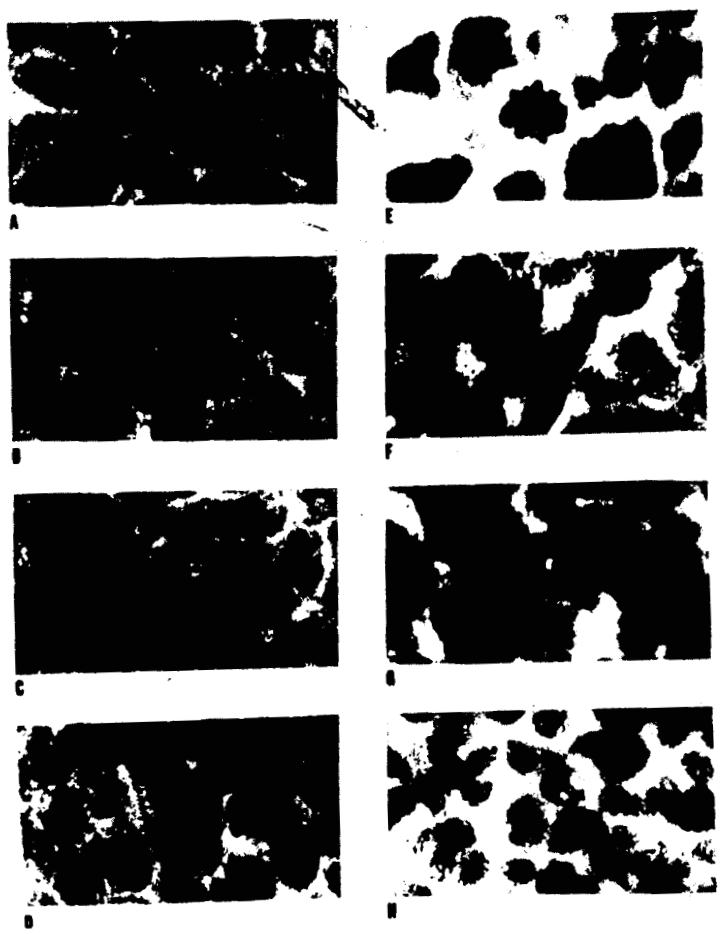

Fig. 8 Figures A through D show the normal mitotic stages of cells in the corneal epithelium. A - Prophase; B - Metaphase; C - Anaphase; D - Telophase. Figures E through H are examples of various types of abnormalitites that occur. Note: the mulberry-like appearance of the nuclei in Figure E and sticky chromosomes in cells that are attempting to separate are shown in Figures G and H.

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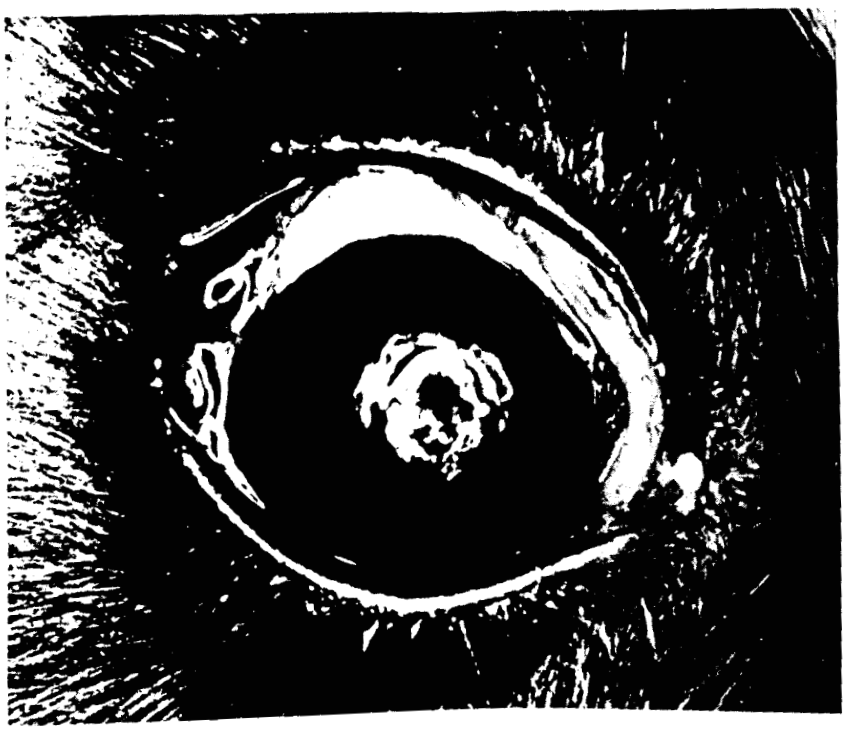

Fig. 9 Burn produced by irradiation at 3 watts for 1 second (15 watts/cm^2) on the cornea of a pigmented rabbit. There is minimal penetration of the cornea and almost no charring. The lesion is well centered, covering the pupil and pupillary margin of the iris. (Athough this lesion may appear to be a cataract in this photograph, it is localized to the anterior corneal stroma only).

Fig. 10 Gross photograph of bisected lenses from rabbit eyes. The lens on the left is normal, while the one on the right clearly shows the concavity of the anterior surface that is found after a nonperforating injury to the cornea on CO_2 laser irradiation. Power, 9 watts. Spot size 0.5 cm diameter. Irradiation time, 1 second.

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