MECHANISMS AND CONTROL OF LASER HAZARDS AND MANAGEMENT OF ACCIDENTS

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The importance of controlling hazards associated with laser systems is increasing as higher energy and power levels become available from the ultra-violet to the infra-red. At the same time the number of people potentially exposed to these hazards is increasing as laser systems are more widely employed in the laboratory, in industry and in field operations. Studies on the biological effects of laser radiation and elucidation of the mechanisms of interaction of high intensity, relatively coherent laser radiation with biological systems provide data pertinent to the meaningful application of lasers to biology and medicine, and of value for demarcation of both long and short term hazards, necessary for the development of safety codes.

The purpose of this presentation is to discuss some of the factors associated with the interaction of laser radiation with biological systems and to provide some recommendations in regard to precautions and management of hazards. The degree to which the various factors contribute to both short and long term hazards of laser radiation cannot be assessed at this time in view of the early stages of the biological studies. However, some recommendations in regard to precautions and management following accidental exposure can be given. These should be considered as tentative since all the potential hazards have not been evaluated or, probably, even recognized, particularly with respect to long term effects. Due to our lack of information, the recommendations may be too stringent, in order to err on the side of safety, and can be relaxed as the field matures.

Analyses of biomedical studies have indicated that the factors responsible for hazards associated with laser systems may arise from:

A. The laser radiation and its interaction with the biological system.

B. The pumping source, especially flash tubes.

C. The high voltage and currents required for the operation of the laser system.

D. The laboratory or field environment in which the system is used.

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A. <u>The Laser Radiation and its Interaction with the Biological System.</u>

Short and long term hazards associated with the beam are dependent upon the properties of the radiation and the biological system. Parameters of the radiation include energy and energy density, power and power density, wavelength and, possibly, coherency and polarization. The characteristics of the biological systems include both the physical and the biological properties of the system. The physical properties include reflectivity, turbidity, electromagnetic and acoustic absorption coefficients, specific heat, thermal conductivity, presence of interfaces and closed cavities, heterogeneity of the tissue and elasticity. Biological characteristics include the biochemical activity, local and general response to injury, the capacity for repair or compensation and the relative sensitivity of the tissue for genetic changes or somatic aberrations (including malignant transformations). Laser radiation of tissue cultures has been shown to result in chromosomal defects which were subsequently transmitted to later generations of cell cultures (1).

The mechanisms which must be considered in the interaction include:

1. Degradation of energy with the production of temperatures sufficient to cause thermal changes per se in the biological system.

2. Degradation of energy within a closed filled cavity (such as within the cranium) accompanied by phase transformations resulting in the production and transmission of pressure and possibly shock waves.

3. The production of sonic, ultrasonic, and hypersonic frequencies.

4. Effects due to alteration of wavelength associated with excitation of molecules and scattering of the primary radiation, as well as frequency multiplication.

5. Induction of photochemical reactions.

6. The formation of free radicals and both charged and uncharged light and heavy particles.

7. The possible importance of high electric field gradients particularly at high peak power densities.

Although degradation of energy with production of temperatures sufficient to cause protein denaturation or thermal burns may be the most immediately obvious gross effect, it is not necessarily the most significant in regard to the short or long term effects. Insofar as the skin is concerned, healing may be accompanied by keloid formation. The possibility of malignant transformation must not be neglected - a higher incidence of squamous cell carcinoma in the region of ald healed scars due to burns is well documented (2,3). Other sequelae of burns include infections, chronic ulceration and scarring with deformities, resulting in limitation of function.

Insofar as the eye is concerned, burns of the retina and choroidal layers at 6943 Å, and at 10,600 Å, can occur at low energy and power levels (4). Burns of these tissues by incoherent radiation have been well documented -- lesions having occurred on looking at the sun during an eclipse (5), or even at a photographic arc lamp. As laser frequencies increase towards the ultra-violet, damage to the cornea can occur at wavelengths shorter than 2950 Å, to which the cornea is relatively opaque. At wavelengths in the infrared, cataracts can be produced, by absorption of the energy by the iris pigment epithelium, with subsequent damage to the underlying lens epithelium and superficial cortical lens fibers by the heat produced. Such cataracts, experimentally produced (6) by focused light on the iris, were limited to the zone of contact between lens and pigment epithelium of the iris, (i. e.

pupillary zone of iris), and did not occur beneath the peripheral (non-contacting) iris. Delayed posterior subcapsular lens changes occurred 60 to 90 days after exposure.

Wether unfocused radiation (i.e. not directly focused on the iris), from either a coherent or incoherent light source, will produce a cataractous change is not yet clear. True thermal cataracts (i.e. the so-called glassblower's cataract) are rare today (7), and are occasionally confused clinically with a more common flocculent deposit on the lens capsule (pseudoexfoliation of the lens capsule), entirely unrelated to infrared exposure. On the other hand, wavelengths in the longer ultra-violet region (2950 Å to 3050 Å) are not known to give rise to cataract formation. These radiations do produce latent (approximately 8 hours) painful, superfical, corneo-conjunctival burns (Kerato-conjunctivitis), which, generally, are easily cleared up with simple treatment. This type of exposure is, perhaps, of greater importance near the continuous operation of gas lasers, where the production of ultra-violet may be very high, and/or the exposure may be long.

Shorter wavelengths of electromagnetic radiation (i.e. x and gamma radiations) not only produce a superficial burn, but they do give rise to cataractous changes, usually after a considerable (measured in months) latent period. Retinal damage is, by far, the most serious of the ocular complications, for such damage is irrepairable. Retinal damage from focused (i.e. inherent dioptrics of the eye) coherent or incoherent light, at minimal or threshold levels, is limited mainly to the pigment epithelium and photoreceptor layers, and is discussed in detail elsewhere (4,8). Moderate to severe levels of irradiation at the retinal surface cause greater destruction of both retinal and choroidal layers, with frequent hemorrhages (Fig. 1) into the vitreous body, with their attendant complications of scarring and even retinal detachment.

Degradation of energy within a closed filled cavity, such as the eye or skull, differs from that occurring on a free surface. Interaction of radiation at a sufficiently high energy density with the media may result in phase transformations to a vapour or gaseous phase. Since the total volume of the cavity is fixed, high pressures will occur at the site of interaction. The pressures will be transmitted with relatively little attenuation to regions distant from the site of interaction, if a quasi-static pressure rise is assumed. This can result in tissue destruction due to direct effects and due to temporary interference or disruption of the vascular supply at some distance from the site of impact. Consequently, severe and fatal injuries can be produced, although the local effect of the initial direct lesions would not be vital to the functioning or survival of the organism.

Studies directed at elucidation of this mechanism of injury have been reported by Fine and Klein (9,10), and Earle et al (11). Following undocused irradiation at 6943 Å, 1 millisecond pulse duration, at energy levels in excess of 40 joules directed at the forehead of mice, death followed within less than 30 seconds in 10 out of 23 animals (9). Intracranial hemorrhages were present in the meningeal spaces, in the ventricles and conducting system, and within the substance at the base of the brain, at regions distant from the site of initial impact (Fig. 2). Irradiation of the exposed brain at equivalent energy levels resulted in a distribution of lesions at the site of primary interaction, rather than the more generalized distribution of lesions at the site of primary interaction, rather than the more generalized distribution of lesions observed on gross and microscopic examination following radiation directed at the closed, intact cavity.

Further studies have been carried out by the authors utilizing pressure transducers to determine the relevance of the previous observations. With the pressure transducer inserted within the closed cranial cavity, a much higher pressure response was obtained than when the pressure transducer was exposed to the same radiation with only skin and a section of skull bone interposed (Fig. 3). Consequently, the effects of irradiation on regions with relatively rigid, closed, filled cavities, on both a macroscopic and microscopic level, differ from those involving regions without rigid boundaries.

Other regions in which injury may be partially dependent on the presence of quasi-static pressure states, on a macroscopic or microscopic level, include the thorax and abdomen. Similar considerations apply to radiation directed at the skin overlying certain anatomical sites, such as the joints, the vertebral column, enclosing the spinal cord and nerves, the anterior, lateral and posterior aspect of the neck (with its subjacent blood vessels, nerves, glands, and trachea) the meatus of the ear, the nares, and other areas where major blood vessels, nerve trunks, or important structures are superficially located (Fig. 4). Damage to these vulnerable areas lying beneath the skin surface may produce severe disability or even death (12).

The presence of sonic frequencies associated with the interaction during laser irradiation of in vivo and in vitro systems has been reported (13). In further studies, both sonic and ultrasonic incoherent pressure vibrations have been detected on non-Q-switched ruby laser irradiation (in the 20 joule range) and on Q-switched irradiation (in the 1 joule range) of heads and chests of mice. On irradiation of the anterior surfaces of the chest and head, these frequencies were observed, when pressure transducers were coupled to the posterior surfaces of mice (Figs. 5,6).

Bubble formation and cavitation may be associated with such vibrations, particularly if a disolved gas is present in the media. Bubble formation can result in the production of free radicals (14). In the case of cavitation, collapse of the cavity in a liquid may result in very high pressures and possibly shock waves in the fluid adjacent to the cavity wall. Incoherent sonic and ultrasonic pressure waves that originate along the path of the beam will result in significant mechanical energy transport to regions distant from the primary source of laser interaction. However, the intensity decreases with distance.

These modes of energy transfer may be of significance, insofar as immediate tissue damage and long term reactive effects are concerned. The importance of such mechanisms will be dependent upon the efficiency of the energy conversion from electromagnetic to mechanical modes and the energy and power density in the beam.

Chiao, Townes, and Stoicheff (15) have shown that irradiation of certain crystals by a 50 megawatt, 30 nsec., ruby laser pulse results in the production of intense (1 kilowatt), coherent, hypersonic waves (10^{10} c.p.s.) via stimulated Brillouin scattering. Studies carried out by Garmire and Townes (16) have shown that, in a similar way, intense, coherent, hypersonic waves can be generated in liquids such as water. Giuliano (17) has investigated damge in dielectric solids caused by hypersonic waves (13 g.c.), which were created via stimulated phonon processes both within the crystal and within the liquids surrounding the crystal. Gigacycle waves are rapidly attenuated, thus giving rise to possible damage only in regions near the laser beam itself.

As the beam is scattered, coherent hypersonic waves will be generated along the beam path. These frequencies may result not only in cell death, but in cell alterations, possibly of long term significance, particularly in the skin and ocular tissues.

The presence of wavelengths other than those of the primary radiation may be of significance, insofar as long term effects are concerned. Irradiation at high energy levels and power densities produces incoherent re-radiation from the excited atoms, some of which occurs at wavelengths shorter than those of the incident wavelength. Should this occur deep to the surface, energy quanta are produced at sites not normally exposed to these wavelengths. This may result in tissue or cellular alterations other than those normally produced. Should these wavelengths lie in the ultraviolet ragion, absorption by nucleic acids and proteins may occur with subsequent long term effects.

Frequency multiplication has been produced in crystals such as quartz and K D P on exposure to laser irradiation at 6943 Å (18,19). Frequency doubling has been observed in amino acid crystals (20). It is possible that frequency doubling may also occur in tissues, particularly in regions where crystalline structures such as melanin granules are present. Should this occur in the skin or eye and in hydroxy-apatite crystals in bone, coherent quanta of energy will be produced at wavelengths which are normally attenuated by intervening tissue layers. In this way, secondary effects, early or delayed, may be produced which differ from those obtained at low radiation levels.

Photochemical reactions may also occur at the wavelength of the primary radiation or at wavelengths produced as secondary phenomena. Because of the relatively high intensity of the radiation, reactions may occur, which would not occur to a significant extent at the same wavelengths at lower energy and power levels. Laser radiation has been shown to induce functional and/or structural changes in proteins, including gamma globulins, enzymes, and other macromolecules of biological origin in vitro and in vivo which may be due in part to photochemical reactions. Such changes have been produced both in the presence or absence of photosensitizing agents acting as energy transfer agents (21).

Photosensitizing agents may be normal endogenous formations (i.e. melanin, hemoglobin, and other chromophores), pathologic endogenous formations (eg. Ochronosis in Alkaptonuria), or may be wholly exogenous (dyes, drugs, vitamins, industrial chemicals). Photo-biological reactions may result in (primary) photo-irritation, or in photosensitization by stimulating immunological incompatibilities with protracted allergic manifestations.

Free radicals have been considered as factors in the biological effects of ionizing radiation, genetic changes and malignant transformation. Electron spin resonance measurements following irradiation of black mouse skin and fibrinolysin preparations indicated with high probability that free radicals are produced in these biological materials on laser irradiation. Irradiated skin of white mice and col-lagenase gave no signal (22). The effects of laser radiation on the incidence of malignant changes in intact mammals is currently under investigation.

The presence of charged particles within the plume ejected from an abdomen of a black mouse has been shown (23). High speed photographs (8,000 - 18,000 frames per second) were taken of the motion of plumes moving through an inhomogeneous magnetic field on laser radiation in the thirty joule range focused on the abdomen of black mice. Spiral plume macroscopic motion and confinement of the luminous part of the plume to a relatively small (1 cm^3) volume was observed (Fig. 7) in agreement with the motion of charged particles moving in an inhomogeneous magnetic field (field strengths 0 - 300 gauss, field gradients of the order of 200 gauss/cm.). Comparison with plumes ejected from the abdomen of black mice on laser irradiation by a focused beam in the thirty joule range in the presence of zero applied magnetic field showed rapid dissipation of the plume over a large volume with no spiral trajectories (Fig. 8). Some variation in trajectory was observed during these studies.

Observations of the decay of plume luminosity also indicate the existance of charged particles within the plume. The plume is self-luminous, since its visibility persists beyond the period of target luminosity and laser pulse duration by at least an order of magnitude. Order of magnitude calculations show the radiational cooling of particles less than 10 microns in diameter to be extremely rapid. Although these particles may be charged, they cannot explain the long persistence of plume luminosity. In general, no other particulate matter of larger diameter was visible with sufficient density in the high speed photographs to be totally responsible for persistence of the visible plume. If the plume contains a high density of ions and electrons, recombination of these constituents is slow enought to explain the persistence of plume luminosity.

Other mechanisms, such as bremsstrahlung may contribute to plume luminosity.

The presence of charged plume particles was substantiated by probe studies. In studies carried out in this laboratory, copper probes initially held at ground potential were positioned near the path of the plume. If the ions and electrons in the plume have unequal directed velocities as the plume expands, a voltage would be induced in the probes. Direct laser irradiation of the probes produced no dectectable probe voltage change. However, during experiments on charged plume particles, precautions were taken to avoid direct irradiation of the probes. Probe voltage changes were detected when copper probes were placed near the path of the plume ejected from various physical and biological targets on irradiation in the 20 joule range. By positioning two probes a measured distance apart along the approximate plume path, a voltage difference or current flow was detected between the two probes as a function of time. This data verified the presence of charged plume particles and allowed an estimate to be made of the average velocity at which the plume expands. Charged particle velocities as high as 10^4 cm/sec. were detected.

Other studies were carried out using streak photography. The plume particle velocities measured with this technique were in agreement with the velocities obtained by probe measurements at some distance from the animal. However, streak photography indicated that observable initial plume particle velocities near the animal surface were at least five times greater than those velocities measured by probes placed at some distance from the irradiated animal surface. An analytic model of the plume indicates that many electron velocities within the plume will exceed the velocity of directed plume motion by at least an order of magnitude (greater than 10^6 cm/sec.). Because the electron mass is extremely small, these velocities represent very low electron energies.

There are several possible mechanisms for ion production within the plume. Ionization can occur on ejection. Ionization can occur just after the plume itself is ejected -- heating being due to continued absorption of laser radiation following ejection from the target. Another possible mechanism for creating charged particles is through inelastic collisions between free electrons and uncharged atoms present in the plume. Elucidation of the actual mechanisms for ionization is currently under investigation.

From the preceeding discussion, the plume ejected from biological material during and following laser irradiation, can be best described as a physical plasma.

The high electromagnetic power densities that are available from lasers, especially Q-switched lasers, indicates that direct field ionization and secondary ionization due to rapid electron acceleration may occur within biological material. A one megawatt per mm^2 beam has an associated electric field of the order of 10^7 volts/meter. Focusing of the usual laser beam to a 1 mm. spot produces strong transverse and longitudinal fields. Bond rupture and direct field ionization may be expected at field strengths of 10^7 volts/meter. Should these effects occur in a certain region, one can expect increased conductivity within that region. However, separation of the effects produced by a high electric field from those due to other energy transformations is difficult.

It is impossible to extrapolate with accuracy the relative importance of the mechanisms of energy transformation at low levels of energy and power on irradiation of small animals, like the mouse, to the potential effects in man at higher energy and power levels. The relative biological significance of the mechanisms discussed is dependent on the degree to which they occur at the various energy and power levels, and their relative effectiveness in producing a specific biological response. The data obtained on severe injuries in "scaled down" systems can, however, serve as guidelines for precautionary measures until their possible implications for larger mammals or man have been critically analysed.

B. Hazards Associated with Flash Tubes.

Hazards associated with flash tubes must be considered, particularly since misfire or accidental firing can occur. Energy density levels of the order of 20 joules per cm^2 can be obtained at the flash tube surface. With unshielded units, the energy density decreases with distance approximately as the inverse square. Addition of a configuration of reflectors will however increase the energy density present at any particular distance from the flash tube.

Ocular damage from low intensity flash lamps of relatively long duration will be determined by the amount of ultraviolet light produced and will be limited mostly to the superficial layers of the conjunctiva and cornea. This form of delayed kerato-conjunctivitis has been mentioned above.

With shorter pulse duration, higher intensity flash lamps, or longer exposure to the low intensity lamps, retinal damage can result. The normal dioptrics of the emmetropic eye increases the power density of the incident radiation on the retina. An energy density of approximately 1.0 joule/cm^2 at the retinal surface (Fig. 1) is enough to produce an ophthalmoscopically visible lesion (4). Special protective glasses (24) designed for radiation within a specific wavelength bank will probably not provide satisfactory protection against broad band flash tube radiation. Flash tube explosion, although uncommon, is another potential hazard for the eyes and body surface and may require proper shielding or protective glasses of another type (i.e. resistant glass either case hardened or laminated).

Long term effects to the eyes due to either a single insult or to cumulative sub-threshold insults are not yet known but continue to present a potential hazard.

Long term hazards to the skin must also not be neglected, in continued testing of exposed flash tubes. Induction of cancer by ultra-violet radiation, shorter than 3200 Å, in animals has been extensively reviewed by Blum (25). In man, much of the evidence for carcinogenesis due to ultra-violet wavelengths is based on epidemiological studies (26); individuals with lightly pigmented skin exposed to solar radiation are more subject to development of skin cancer, including melanomas, than those with well melanized skin. Cancer of the skin is more prevalent in regions with greater exposure to sunlight.

Consequently, considerable care should be taken during flash tube testing, both insofar as the eyes and the skin are concerned.

C. Electrical Hazards.

Hazards related to laser systems are associated not only with the laser beam, but with the laser equipment per se. The large energies stored at high voltages in the capacitor bank are dangerous (27,28). Discharge of the bank can occur due to direct contact with a bank which has been improperly interlocked, in which the discharge circuit is not operational, or which has not completely discharged at the time of contact. A further hazard arises when the bank is in an area physically separated from the control system. In a large installation, modifications to the capacitor bank complex may be attempted by one group while a second group is attempting to use the unit for investigative purposes. This has occurred in parallel fields. A third hazard is associated with the high voltage current carrying cables. Flaws in cable insulation, occurring in the manufacture, or continued use of the cable will be extremely hazardous. Individuals or equipment may be physically located adjacent to the cable, while high voltage exists on the cable. This represents a marked hazard to personnel, which can be avoided by proper procedures.

Electrical shock can result in severe burns, pain, muscular contractions, trauma due to involuntary movement of the individual and death. Death may be due to respiratory arrest dependent on severe continued contraction of the respiratory muscles or involvement of the central and/or peripheral nervous system. It may be due to ventricular fibrillation. Experimental data for shock threshold to cause cardiac fibrillation in man must be extrapolated from studies on animals. Studies on fibrillation thresholds to 60 cycle current were reviewed by Dalziel et al (27,28). Electrolysis of deep tissue can occur, and injury to vessel walls can result in delayed hemorrhage (29).

D. The Laboratory or Field Environment.

Some hazards associated with laser systems are dependent on the specific environment in which they are used. Poor lighting, highly reflecting walls and other surfaces, improper positioning of the laser system and associated equipment directly towards entrance areas, the presence of transparent glass in doors and windows through which direct and back-scattered radiation can pass with little attenuation, present obvious hazards. Insufficient temperature control of the environment may result in sweating by the individual, with concommitant decrease in electrical resistance of the body and resultant increase in the electrical hazards. Considerable dust or smoke may result in scattering of the radiation from other than the usual surfaces.

In the field, hazards affecting the operator and other personnel may arise from scatter due to terain, particulate matter, fog, snow or rain. Electrical hazards may be accentuated by decrease in electrical insulation of the system due to several of the above factors and due to bacterial or fungal attack on the equipment.

Control of Laser Hazards and Management of Accidents.

Consideration of the mechanisms of laser interaction with biological systems discussed above and the biological effects, reported elsewhere has led to a tentative outline of a program for the control of laser hazards, and management of laser accidents.

A. Control of Laser Hazards
  1. General Administrative Procedures
    a. Personnel
      (i) Laser Hazard Control Officer
      (ii) Deputy Laser Hazard Control Officer
      (iii) Laboratory Laser Hazard Control Officer
    b. Medical Supervision
    c. Records
  2. Laboratory Design and Operation
  3. Protection Standards and Dosimetry
B. Management of Laser Accidents.

A. Control of Laser Hazards.

1. General Administrative Procedures.

a. Personnel

(i) Laser Hazard Control Officer

The laser hazard control officer should be responsible for all factors associated with laser safety within the organization. He should be responsible only to the senior management of chief executive officer of the organization, and should carry authority regarding laser safety which can be countermanded only by the chief executive officer.

He should have full records concerning all studies using lasers carried out within the organization, as well as information concerning personnel and the characteristics of the equipment. He is responsible for monitoring laser equipment or associated experiments, assessing hazards to the extent feasible and providing safeguards. Information regarding proposed experiments should be forwarded to him in writing in order that he be able to assess potential hazards prior to their introduction.

He should provide information regarding installation of new systems, be present during the intiial operation of a laser system or during major modifications of experiments in progress.

He is responsible for instruction in laser safety of all personnel associated with laser studies. He should be available and notified in the event of any laser accident.

The Laser Hazard Control Officer may be a medical officer, trained in laser hazard control, or an engineer, interested in general safety with cognizance of laser hazards.

(ii) Deputy Laser Hazard Control Officer.

Since the Laser Hazard Control Officer may be absent or unavailable, a Deputy Laser Hazard Control Officer should be appointed (to act in his place as a substitute for the former when he is not available).

(iii) Laboratory Laser Hazard Control Officer.

All laboratory areas should have an individual designated as a safety officer for that area. He is to report to the Laser Hazard Control Officer insofar as laser safety is concerned. He is responsible for the day to day safety within the laboratory and maintenance of adequate records regarding compliance with the safety standards.

b. Medical Supervision.

The purposes of medical supervision are to deal with the medical and medico-legal aspects of laser hazards. Since the long term hazards are unknown, a balance must be achieved between possibly applicable procedures and those which can be considered practical.

Medical supervision should include an initial medical examination. The history should emphasize previous radiation exposures and aspects associated with the eyes and skin. The physical examination should give more than usual attention to the eyes and skin, and should be accompanied by laboratory studies. Follow up studies should be carried out periodically at 3 to 6 month intervals and following an accident.

(i) Radiation Exposure History

A history should be ovtained regarding previous exposure to laser radiation, to high intensity radiation in the radio frequency or microwave regions, and to ultraviolet, x-ray, gamma ray or particulate radiation. Records of previous radiation exposure should be obtained.

(ii) General Medical History.

Particular attention should be paid to a previous history of injury, infection or inflammation of the eyes or visual disturbances. Attention to the skin should include information regarding allergy, photosensitivity, previous surgical excisions, or abnormal wound healing.

(iii) Physical Examination.

The physical examination should include a complete ophthalmologic and dermatologic evaluation. The eye examination should of course include the usual tests of visual acuity, refraction, slit lamp examination and a careful ophthalmoloscopic examination under full mydriasis with both white and red free light. Screening of the critical areas of the macula and fovea by either routine tangent screen examination or campimetry is too tedious and generally not practical. One rapid method of screening this important central area and one which may be carried out quickly and simply by a technician or trained aide is the use of an Amsler grid. A negative screening here adds to the strength of a negative routine type of examination. These special tests may be reserved for evaluation of lesions detected by other means.

Fundus photography is probably not, in general, useful as a routine screening procedure unless an ophthalmoscopically detectable lesion or other eye pathology is found. Photographic recording of this lesion may then be of considerable value. Fundus photography may, however, provide a baseline for evaluation of progression of any visible lesion which may develop . Evaluation of a foveal lesion should be done with great care, for eclipse burns frequently produce ophthalmoscopically detectable lesions in the foveal area with no apparent defect in the central visual acuity.

The dermatologic examination should include particular attention towards the presence of keratoses and skin malignancies, as well as benign dermatoses, particularly those related to photosensitization.

(iv) Laboratory Studies.

These should include a complete blood count, routine urinanalysis, and blood smear.

c. Records.

Adequate records should be kept regarding:

(i) Personnel

(ii) Characteristics of the laser facilities within the organization.

(iii) Operation of laser facilities

(iv) Accidents.

2. Laboratory Design and Operation.

The attention which should be directed towards laboratory design and operation is dependent on the energy, power levels and wavelengths used. Should high energy or high power equipment be used, the operations area should be separated from the charging bank and from the laser output area. Under these circumstances interlocks are required to prevent individuals from entering the laser firing area or the capacitor bank area, during charging of the bank or firing of the unit. Information concerning the laser beam interaction can be obtained using closed circuit television systems or photography of either the interaction or the meter measurements necessary within the beam area. A sign indicating that the area is a laser laboratory should be posted at the entrance of the laboratory. A dual set of visual signals switching from green to red can be used to enhance safety during operation of the laser equipment. The dual system enhances the reliability of the safety system, since one visual signal such as a light must be on and the other off at all times. With a single light signal, it is not known whether the laser is not being operated, or the light has burned out. Auditory signals, in some cases, may detract from rather than add to safety, particularly since dual auditory systems are impractical.

There should be sufficient isolation between various laser units operated in the same area, to prevent exposure of personnel to radiation from other laser areas. Enclosure of the laser head, the irradiation site and the space between them (when feasible), will assist in reduction of hazards.

The room should be well lighted to minimize pupil diameter and consequent light absorption by the eye. Painting or coating of the walls with a fire resistant material which will absorb at the laser wavelength used will be of value. Full reliance should not be placed on laser glasses during operation since interaction of the beam with material may result in backscattered radiation at wavelengths other than those of the incident radiation, at which the attenuation factor of the glasses may be low. This is of particular significance since the effects of long term cumulative radiation wxposure are unknown. Another factor which will limit the effectiveness of glasses is that the radiation is not scattered in a mathematically predictable manner, and in some instances may be scattered predominantly in a specific direction. Glasses that have been directly exposed to unusually high intensity radiation should be discarded since their effectiveness may be degraded, without obvious gross defects. Consequently, it is preferable to avoid looking at the beam or back-scattered radiation rather than depending on glasses. A count-down procedure during operation of the laser should be used.

At ultra-violet and infrared wavelengths the problem is accentuated since the beam is not visible. Consequently, either the beam should be enclosed, or the area so arranged that an individual cannot either pass through the direct beam, or be subject to scattered radiation. This may require the use of shielding. The area should be monitored before and after shielding to determine the radiation distribution. This problem is particularly acute with continuous, high power lasers, since constant monitoring of the area by an individual throughout the on time of the beam is impractical. With semiconductor lasers, the problem of strong off-axis peaks must be recognized. In both these cases, monitoring is required to determine the radiation levels in all regions of the room.

Although definitive information concerning hazards associated with the capacitor discharge system has [illegible] sufficient data has been accumulated on electrical hazards [illegible] arising from the high energy system (27, [illegible] resistors on the capacitor bank are used, it is important to note that time constants are involved, and the discharge system may fail. Manual discharge using a grounding rod should therefore be used as a back up device prior to contact with the capacitor bank. These grounding rods with visible grounding should be associated with each bank.

The cables from the power supply to the laser head should be placed so that accidental contact with them cannot occur, since these cables carry high current at high voltage. Equipment such as oscilloscopes should be so placed that the observed is not required to turn or face towards the beam during charging of the bank and firing of the laser. Meters which measure high voltages, and oscilloscopes associated with the laser euqipment and with the experiments should be so arranged and protected as to present minimal hazards to the investigators.

The placement of firing buttons must be at a distance from those of the charge or hold buttons in order to prevent accidental discharge of the laser through pressing of the wrong button. Unless automatic recharge of the capacitor bank is required for experimental purposes, charging should be under manual control, and not automatic.

Capacitor discharge through other than the usual discharge circuit including discharge due to capacitor breakdown may occur. Hazards associated with this can be minimized by the use of distance and mechanical shielding between the operator and the bank. Discharge of a bank due to capacitor breakdown may be accompanied by a loud sound - this can be minimized by sectionalizing the bank and by sound damping techniques.

Other factors include the usual ones of responsibility and authority being vested in one individual (Laboratory Laser Hazard Control Officer) insofar as making certain that the area is secure prior to operation of the unit. He should be responsible for charging the bank and firing the unit. Working in pairs is important. The safety procedures, precautions to be taken, techniques for mouth to mouth resuscitation, the names, addresses and telephone numbers of the physician, Laser Hazard Control Officer, and the ophthalmologist should be posted.

3. Protection Standards and Dosimetry.

Due to the incompleteness of our knowledge concerning biological effects, particularly with regard to long term effects, it is not possible to set firm standards at this time. A useful guideline for protection insofar as immediate or short term effects is concerned, is the minimal threshold dose of radiation required to produce injury.

Considerable attention has been directed towards determination of threshold doses of pulsed laser radiation for damage to the eye, particularly with respect to injury to the retina-choroidal layers. Biological variability including heterogeneity, pigmentation and blood supply and extrapolation of studies on animals to man are factors which must be considered. The threshold value obtained will be dependent on the method used. Such methods include ophthalmoscopic examination and photography, microscopic studies, histochemical and enzymatic techniques, electron microscopic investigation and the measurement of electrical changes by electroretinography. Studies on the eyes to determine threshold effects have been carried out by William T. Ham, Jr., (30), Walter Geeraets (4), Ben S. Fine (8), and Milton Zaret et al (31). In general, the threshold dose at 6943 Å, non-Q-switched, millisecond exposure, for damage to the retina is in the range 0.5 to 1 joule per cm^2 incident at the retina. The energy required to produce threshold [illegible] with decreasing pulse duration (4).

In our studies, the threshold dose for gross visible damage to the skin of mice appears to be one order of magnitude higher than that for the eye. This difference may be due to reflectivity, scatter and diathermanous properties of the skin of mice, as well as biological factors. A lower skin threshold dose was obtained at high peak power levels with Q-switched systems as compared to thresholds at longer pulse durations (32).

This data in conjunction with a safety factor of at least 100, provides guidelines for radiation protection standards, at the ruby wavelength.

Order of magnitude calculations indicate that direct viewing of even a 1 milliwatt gas laser at 6328 Å is extremely hazardous. Consequently, considerable care should be taken in adjustment of even low power gas lasers.

Standards with respect to high voltage electrical equipment should comply with acceptable standards of electrical engineering including those of the A.S.T.M., A.S.A., and I.E.E.E. and are referenced in Electrical Engineering Handbooks (33). The specifications set by the appropriate agencies must be complied with for systems to be used in the field.

Dosimetry of two types is desirable. One, incorporating a photodetector, would measure instantaneous radiation intensity, for protective purposes, the other would measure cumulative exposure for medico-legal as well as medical purposes. These two types of dosimetry are used for personnel exposed to X and gamma radiation. Dosimetry protection for a single pulse is not feasible, because of the short pulse duration. Further development of adaptive filter glasses may provide some protection. The former type of dosimeter can, however, provide information regarding radiation intensity at a point, for succeeding pulses, or for continuously operating units. Although there are a number of problems associated with the latter type of dosimeter, it offers a means for maintaining exposure below maximum permissible dose levels.

B. <u>Management of Accidents</u>.

First aid should be restricted to minimal, essential manipulation of the patient as required for arrest of hemorrhage, coverage of the affected region with sterile gauze, and immobilization of the affected region, particularly in the event of fracture following electric shock. In the case of respiratory arrest, mouth to mouth artificial respiration should be immediately begun, and continued until medical attention is obtained. The equipment, techniques and knowledge necessary to apply controlled counter-shock in the short period available if ventricular fibrillation occurs and to attempt pacemaking is not available in the field. Consideration can be given to maintenance of cardiac output by external massage. All accidents should receive immediate medical attention. An ophthalmologist should be on call at all times. A general physician, also on call at all times, should be available for accidents involving regions other than the eye. Their phone numbers should be posted in the laboratory.

Since specific treatment of the laser induced injury is not available, medical management of the immediate injury will follow the usual procedures for the treatment of traumatic lesions of comparable degrees of severity.

Retinal damage, as previously mentioned, is irreversible and medical care consists mainly in evaluation of the damage and prevention or treatment of possible complications. Surface burns due to [illegible] light are generally simply cared for with topical medications but a severe [illegible] resulting from impact of strong radiation on the iris [illegible] and perhaps even systemic steroids to control [illegible]

Follow up should be carried out with particular attention to delayed anatomical and functional disturbances of the eye and to the possible late manifestations of chronic inflammatory changes in the skin and deeper structures.

The delayed effects in the skin and subcutaneous tissues may include scarring, atrophy, indolent ulcers, persisting sinuses, chronic granuloma, and possibly malignant transformations. Treatment of these late sequelae should be in accordance with established dermatological methods of management.

Accidents involving particularly sensitive sites, such as joints, cranium, superficially located blood vessels and nerves, require the immediate attention of the respective medical specialists. The experimental findings, as discussed indicate that trauma to these regions cannot be assessed on the basis of the extent of the superficial injury; the patient should consequently be carefully followed in the event of injury to these regions.

Each accident should be reported to the Laser Hazard Control Officer (L.H.C.O.) as well as to the attending physician. Abstracts of the medical records should be made abailable to the L.H.C.O.

SUMMARY

Energy transformations associated with the interaction of laser radiation with biological systems has been discussed. Further study (at various energy and power levels, and wavelengths) directed towards elucidation of the mechanisms of energy transformation is required. The relative significance of these energy transformations insofar as short and long term biological effects are concerned is dependent on the parameters of the radiation, and the properties of the biological system. Hazards associated with the operation of laser systems other than those due to the radiation, per se have been considered. Some recommendations have been presented regarding control of hazards and management of accidents. Further investigations on the biological effects of laser radiation will result in a better understanding of the short and long term hazards, and provide a basis for more definitive recommendations regarding hazard control and accident management.

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FIGURE 1

Fundus photograph of a pigmented rabbit eye showing four almost uniform lesions produced by a pulsed ruby rod laser. The exposure at the retinal surface for these lesions was approximately 1.0 joules/cm^2. The larger lesion to the left of the uppermost mild lesion has a hemorrhagic center and was produced by a retinal density of approximately 10 joules/cm^2. A third insult, produced by approximately 0.1 joules/cm^2 at the retinal surface to the right of the uppermost mild lesion is not ophthalmoscopically visible. - Courtesy of Dr. R.W. Neidlinger, Ophthalmology Service, Walter Reed General Hospital, Washington, D.C.

FIGURE 2(a)

Effects of unfocused non-Q-switched 6943 Å, 60 joules (60 joules/cm^2) laser radiation on the shaved skin surface of the forehead of a mouse.

FIGURE 2(b)

Cross section [illegible] laser irradiation of forehead [illegible] the ventricles, the con[illegible]

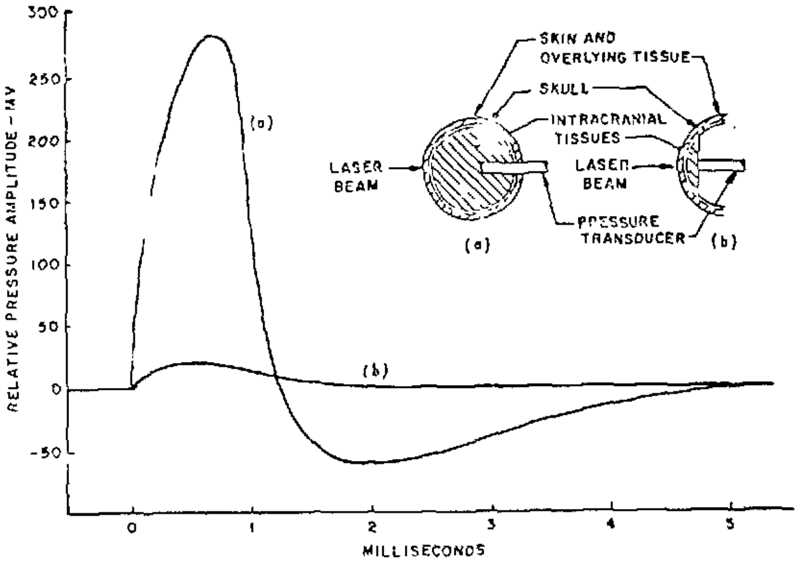

FIGURE 3

Comparison of relative pressure amplitude within the enclosed cranial cavity and pressure amplitude within the cranium with free boundaries. Irradiation at 6943 Å, 25 joules/cm^2, unfocused.

FIGURE 4

Edema and swelling in knee region following non-Q-switched irradiation at [illegible]

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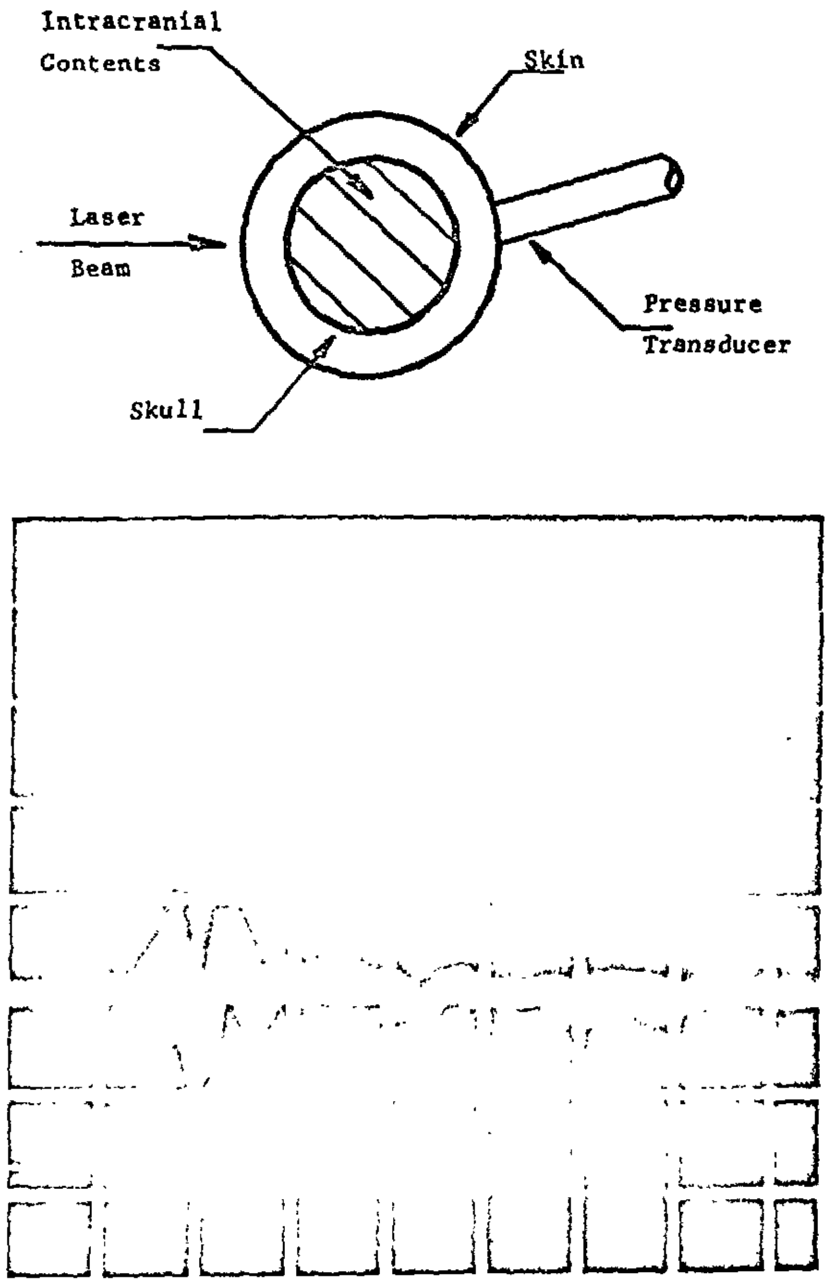

FIGURE 5

Sonic frequencies produced on non-Q-switched ruby laser irradiation of the shaved forehead of mice. Ordinate axis: 0.02 v/cm. (relative pressure amplitude) Abcissa axis: 0.5 msec/cm.

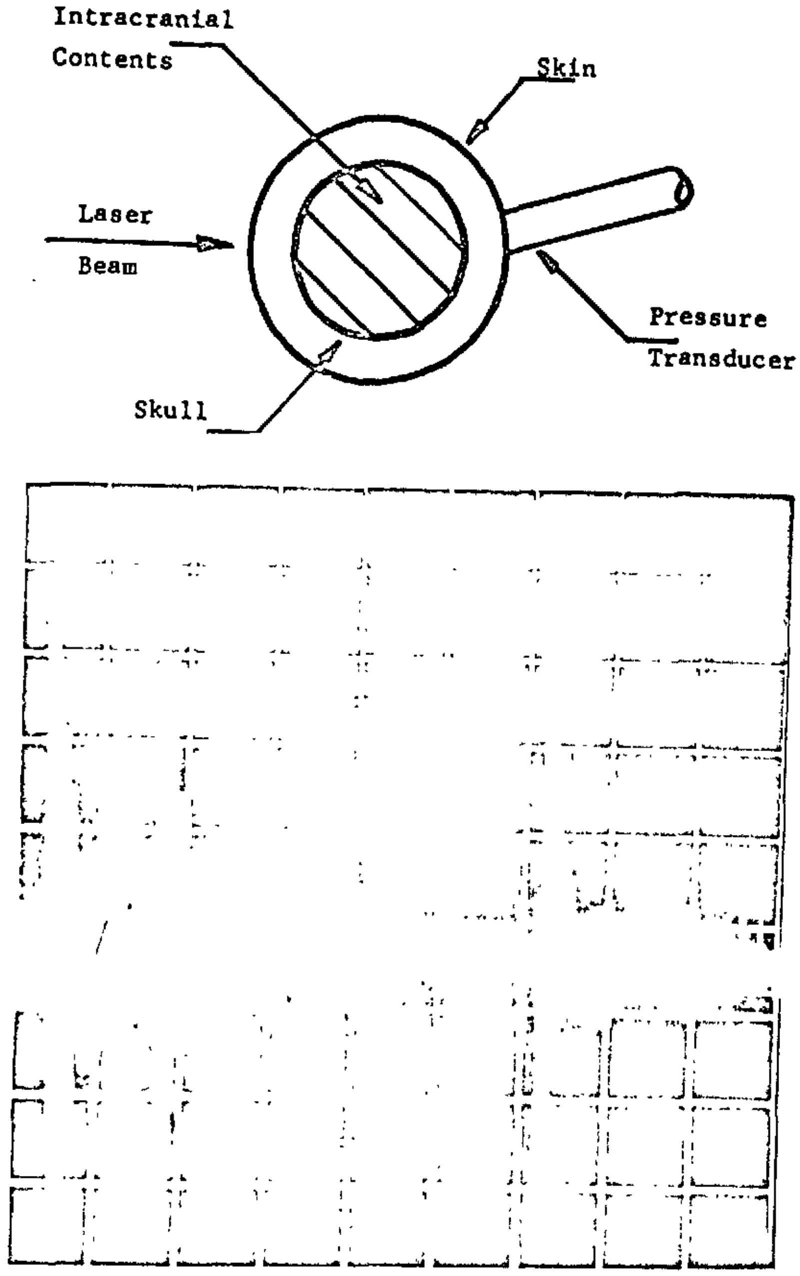

FIGURE 6

Ultrasonic frequencies produced on 1 joule Q-switched ruby laser irradiation of the shaved forehead of mice. Ordinate axis: 0.05 v/cm (relative pressure amplitude) Abcissa axis: 50μ sec/cm. Three spikes produced on Q-switching.

FIGURE 7

Spiral plume trajectory from abdomen of mouse on application of a magnetic field. Irradiation at 6943 Å, 30 joules, non-Q-switched, focused. Single frame of film taken at 8,000 frames per second.

FIGURE 8

Linearly directed plume and outward hemispherical distension of abdominal skin of mouse, irradiation at 60 joules at 6943 Å focused.