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**EDGEWOOD ARSENAL**
**TECHNICAL REPORT**

**EATR 4005**

# *Evaluation of the Mechanism of Some Physical Effects of Lasers on Tissue*

by

Janice A. Mendelson, Lt Col, MC
Norman D. Cook
James R. Dearman

August 1966

**Biophysics Laboratory**
**Research Laboratories**
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**EDGEWOOD ARSENAL, MARYLAND 21010**

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EDGEWOOD ARSENAL TECHNICAL REPORT

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# EVALUATION OF THE MECHANISM OF SOME PHYSICAL EFFECTS OF LASERS ON TISSUE

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Project 1M012501A027

**Biophysics Laboratory**
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## FOREWORD

The work described in this report was authorized under Project 1M012501A027, Wound Ballistics (U). The experimental data are contained in notebook MN-1665. This work was started in July 1963 and completed in October 1965.

In conducting the research described in this report, the investigators adhered to the "Principles of Laboratory Animal Care" as established by the National Society of Medical Research.



### Acknowledgments

The previously unpublished portions of this work utilized the laser facilities of the Applied Physics Branch, Electromagnetics Laboratory, US Army Missile Systems Command, Redstone Arsenal, Alabama. The following individuals from US Army Missile Support Command, Redstone Arsenal, rendered very capable assistance: Lt Philip D. Standly, VC (Veterinarian Service), Joseph L. Meadows (Pictorial Division), and Howard H. Gates (Pictorial Division). Lt John C. Burr, Jr., and Donald J. Green, Physical Science Laboratory, US Army Missile Systems Command, provided the "Q-spoil" laser shots in the previously unreported portions of this work. A preliminary comparison of the laser and "Bovie" on the same tissue was the result of the kind cooperation of Drs. John P. Minton, Robert C. Hoye, and Fitzhugh X. Mullins, National Cancer Institute, National Institutes of Health, who permitted us to work with them for this purpose.

Pathological examinations were done by Capt Martin R. Krigman, MC, Wound Pathology Department, Biophysics Laboratory. Pressure waves were measured with a transducer that was made and calibrated by Mr. B. Granath, US Army Ballistics Research Laboratories, Aberdeen Proving Ground. Grateful acknowledgment is made of the advice and assistance of Mr. David Grossman, Chief, Research Instruments Department, Biophysics Laboratory.

## DIGEST

The purpose of these studies was to determine whether there is any significant hazard to man accidentally exposed to a laser beam striking elsewhere than the eyes. All of this work concerns acute injury of surgical significance. It does not consider possible alterations of cellular metabolism following single or repeated exposures or other effects of chronic exposure.

Experimental results using freshly excised tissue from various species, as well as intact anesthetized animals, agreed with predicted results based on known physical principles. A neodymium-doped, glass laser rod delivering approximately 700 joules in 2 msec in a spot size ranging from 0.48 to 2.0 cm, depending on the lens employed, and a "Q-spoil" laser delivering about 3 joules with about $10^7$ w maximum peak power were utilized.

The penetrability of the laser beam, like any light, is affected by the characteristics of the medium through which it passes. On passing through tissue, the light is attenuated and becomes diffused, losing both temporal and spatial coherence because of the nonhomogeneity of tissue. Some of the incident energy is also lost by reflection, the amount depending on the surface characteristics. At present, energy densities sufficient to produce effects greater than singeing cannot be achieved without the use of a lens system. When the lens is introduced, the parallel nature of the light rays is removed, so that from this point on, the light follows the optical principles that apply to any lens system. The more transparent the tissue, the deeper within it the light can be brought to a focus, but, because of the several factors that tend to reduce energy density on passage through tissue, energy density sufficient to produce visible damage remains limited to a few millimeters in depth in tissues such as skin, muscle, bone, and solid organs.

The severity of the burn produced is related to both the duration of exposure and the amount of energy. The short durations of pulsed laser energy do not permit significant heat conduction to occur in tissue. When the energy is high enough, the tissue is vaporized; when it is lower, coagulation necrosis occurs. These effects are sharply localized.

When the rate of application of energy is exceedingly rapid, as in the use of the "Q-spoil" laser, a shock wave is produced at the point of impact. This pressure wave is rapidly attenuated on passage through tissue, so that the resulting forces are not great enough to produce damage of surgical significance in nonocular tissue of intact man and large animals. This was ascertained by using specially made, highly sensitive, pressure transducers calibrated so that the intensity of the pressure waves could be measured.

The vaporization of tissue at the point of contact produces a jet of vapor that is capable of inflicting mechanical trauma. When this "plume" is free to escape to the outside, the damage to the adjacent tissues is minimal. Except in the eye, the body wall of man is too thick to permit enough energy density within the tissue for heating to the point of vaporization to occur deep to the body wall. This differs from thin-walled small animals, in which it is possible to achieve damage to underlying structures as the result of the few millimeters of penetration of laser beams that maintain sufficiently high energy density to be destructive.

The type of "lesion" produced by the laser can probably be simulated by other sources of brief application of high amounts of energy, as indicated by the similarity of certain high-frequency-current injuries (for example, cutting "Bovie") to laser lesions.

In conclusion, except for the eyes, from a surgical standpoint, there is no reason to expect other than superficial damage from accidental exposure of man or large animals to lasers. Experimental data tend to confirm the theoretical principles involved.

## CONTENTS

# EVALUATION OF THE MECHANISM OF SOME PHYSICAL EFFECTS OF LASERS ON TISSUE

## I. INTRODUCTION.

The purpose of our studies has been to determine whether there is any significant hazard to man if he should accidentally stand in front of a laser striking elsewhere than the eyes. All of the emphasis in this work concerns acute injury of surgical significance. It does not consider possible alterations of cellular metabolism following single or repeated exposures, which would be of interest in studies of carcinogenesis, or other effects of chronic exposure.

As is true with many new scientific discoveries, there is a tendency to regard the laser as some sort of magic. This attitude is reminiscent of the days shortly following the discovery of the X-ray, when there was much clamor in the public press about the possibility that people would no longer have privacy in their own homes because X-rays would permit nosy neighbors to look through the walls!

The operation of a laser (light amplification by the stimulated emission of radiation) follows known scientific principles, and many of its effects can be predicted by the application of basic physics.

The emission from lasers is in that region of the electromagnetic spectrum commonly referred to as the "light" region, which extends from the ultraviolet through the infrared. The wavelength of the emission depends upon the type of laser being used. Ruby and neodymium-doped glass are the laser materials most capable of producing gross tissue destruction in a short time. The ruby has an output emission of 6,943Å in the visible part of the spectrum, and neodymium glass has an output emission of 10,600Å, which is in the near infrared. Ruby emission seems to have a greater thermal effect on tissue than the neodymium-glass emission at the same energy density (joules/sq cm). This may be attributed to the higher photon energy at the shorter wavelength of ruby emission compared to the photon energy at the longer neodymium wavelength, as shown by $E = hc/\lambda$, where $E$ = photon energy, $h$ = Planck's constant, $c$ = the speed of light, and $\lambda$ = the wavelength. The ruby, however, because of its low efficiency (generally 0.5% to 1%) and limited sizes, does not produce the high-energy bursts of radiation of which neodymium glass is capable. (The efficiency of neodymium is generally from 3% to 5%, with physical sizes up to 6 ft in length.) Higher energy emissions from the laser rods do not necessarily mean greater tissue damage or even greater penetration. Tissue damage is related to the energy <u>density</u>, which is obtained by bringing the laser beam to a focus using various types of lenses. It is also related to the absorption characteristics of tissue, which absorbs some wavelengths more readily than others. According to Hardy and Stolwijk,[1,2] ultraviolet wavelengths are absorbed in the very superficial layers of the skin, and the longer infrared wavelengths may penetrate further; however, X-rays, which are of shorter wavelengths than both, penetrate the farthest.

## II. PENETRABILITY OF LASER LIGHT.

The penetrability of the laser beam is affected by several factors.

### A. Characteristics of the Medium.

#### 1. Attenuation.

The high degree of coherency (small beam spread) of a laser beam permits much greater brightness (w/sq cm/steradian) at the target than can be obtained from a noncoherent source of light, because there is less loss by divergence of the rays. A laser beam is capable of traveling hundreds of thousands of miles through space,[3] although its intensity is reduced by scattering and absorption upon reaching a distant target. Attenuation, however, is much greater through other media. The spatial attenuation follows a predictable curve based on the characteristics of the medium through which the laser light travels. The equation for this curve is $I = I_0 e^{-\mu x}$, where $I$ = intensity at some distance $x$, $I_0$ = initial intensity, $\mu$ = loss coefficient of the medium, and $x$ = distance traversed through the medium.

#### 2. Dispersion and Diffusion.

As laser emissions are highly coherent and monochromatic, they do not suffer the intensity losses from dispersion that may occur from other sources of light. When the laser beam passes through a nonhomogenous medium, however, both temporal and spatial coherence will be lost. This is because the component rays are deflected on entering and exiting portions of the nonhomogenous structure that have different indexes of refraction. When light passes through a translucent medium, the beam will be scattered because of the irregular planes within the medium and, consequently, the effectiveness of the laser beam for deeper penetration will be reduced.

Tissue, being nonhomogenous and containing numerous structures such as capillaries, nerve fibers, and connective tissue, causes diffusion of light. Therefore, after entering it, the laser beam will lose much of its directionality. This reduction of energy density results in a shallower penetration of the tissue than one might otherwise expect.

3. Reflectivity.

A white or highly polished surface will reflect more laser light than a dark surface, and, therefore, it will reduce the amount of energy available to penetrate the target.

4. Transparency.

Laser light striking a surface that is opaque to its wavelength is confined to the surface and its immediate vicinity. The depth of penetration is, of course, greater in a heat-absorbing material such as metal. If, however, the target is transparent or translucent, laser light can pass into it, but unless the medium is completely homogenous, the rays will lose some of their spatial and temporal coherence because of scattering, so the energy density will be reduced.

5. Absorption Characteristics.

The pinkish color of human or mammalian tissue, such as muscle or skin, indicates that it tends to act as a red filter. Therefore, depending on the transparency of the tissue, red and infrared light would tend to pass through it with less attenuation per unit distance than blue or green light. In so doing, red and infrared light give up less energy per unit distance (less energy is absorbed by the tissues) than the other wavelengths. Black absorbs light. Therefore, when a laser emission strikes areas of dark pigment (other than red), the energy tends to be used up at the point of contact, producing a more intense reaction at that point but leaving less residual energy for penetration.

Many studies of the penetration of light rays into the skin have been made. These have included ultraviolet, visible, and infrared wavelengths. This subject has been investigated by dermatologists interested in sunburn protection, as well as scientists concerned with flash burns from nuclear weapons.[1, 2, 4, 5] These studies indicate that the skin absorbs practically all of these wavelengths within its superficial layers. Stolwijk and Hardy[2] have stated that, on exposure to light containing visible, infrared, and ultraviolet wavelengths, "most of the radiation is absorbed in the first 0.05 to 0.15 mm of skin through combined effects of absorption and scattering."

B. Focusing.

Although the high-energy laser emission is collimated, the beam diameter may be so large that it is hard to achieve enough energy density to have a marked effect on the surface of a target. At present, energy densities sufficient to produce effects greater than singeing of tissue cannot be achieved without the use of a lens system. (Some continuous gas lasers are theoretically capable of producing a burn, but, because of the length of time involved, it is unlikely that someone would accidentally stand in front of them long enough and quietly enough to achieve more than a superficial effect.) To create the maximum energy density necessary to achieve the maximum effect on the target, lenses are interposed between the laser head and the target to focus the beam to a much smaller area. For instance, decreasing a 1-cm-diameter spot size to 1 mm increases the energy density by a factor of 100. As soon as the lens is introduced into the system, however, the parallel nature of the light rays is removed, and the light now follows the optical principles that apply to any lens system. When the lens is interposed, practically all of the light rays begin to diverge after passing through the circle of least confusion (at the focal point of the lens), so that the energy density rapidly decreases with distance from the lens. The angle of divergence depends inversely on the focal length of the lens, and the energy density (or light intensity) is progressively reduced with increasing distance from the focal point. This creates a limit to the energy that can be delivered into the depth of a target. Even under optimum conditions of transmission, this limit cannot be exceeded. For instance, 100 joules in a 1-mm-diameter spot at the focal point may be only 10 joules/mm 10 cm away, depending on the lens used. The longer the focal length, the less critical the focus need be and the less alteration in energy density with distance from the focal point.

The pattern of laser light striking a translucent target tends to have a conical shape anyway, because (especially with the very high energy sources) edge effects create a halo of noncoherent rays of energy density which are more easily diffused. Concentric bands of different degrees of damage in skin of animals have been observed by other investigators,[6] and this pattern is seen on exposed Polaroid film placed in the path of a high-energy laser beam.

Theoretically, with a perfect lens and a truly collimated source, the spot size should not be dependent on the focal length of the lens. Because neither the collimation nor the lens is perfect, however, the shorter the focal length, the smaller the spot size that can be obtained. For instance, with the approximately 700 joules output from the neodymium-doped glass laser used in our most recent studies, the total spot size ranged from 0.48 cm for the 30-mm-focal-length lens to 2.0 cm for the 125-mm lens. Most of the tests were done with an 89-mm-focal-length lens that gave a total spot size of 1.42 cm. The actual energy on target for each shot was determined with the use of a TRG Model 100 thermopile and a beam splitter. Because of edge effects, approximately one-half of the total energy output was contained in a circle the diameter of which is the central fourth of the total spot size.

It is possible to reduce the spot size with a focusing lens and to restore the parallel nature of the rays with a plano-convex lens, but sufficient energy densities for grossly destructive effects are not achieved. With the use of a lens system or without it, in the instance of an opaque target, the laser action will be confined to the surface and its immediate vicinity. If the target is transparent or translucent, the light will be able to penetrate farther, and, even though there is considerable loss by reflection and scatter, it is possible to bring the residual light to a focus deep in the material. The difference is illustrated in figure A1, appendix, which shows the laser striking a Bakelite target, and in figure A2, appendix, which shows the effect on a Lucite target. (All figures, A1 through A12, are in the appendix.)

In studying light penetration, a block of skin, subcutaneous fat, and muscle from the thigh of a 36-lb, male, Jersey Duroc hog was tested. The total thickness of the block of tissue was 37.5 mm; the skin measured 2.5 mm, the fat 10.0 mm, and the muscle 25.0 mm. The 30-mm-focal-length lens was used for some "shots" and the 89-mm lens for others, so that the total spot size was 0.5 to 1.4 cm. The total output in these spot sizes ranged from 410 to 515 joules. In some instances, the surface of the skin was at the focal length of the lens, and, in others, it was 15 mm closer to the lens, to permit focus deep to the surface. In none of these tests did a detectable amount of light pass through the target.

Similar studies were done on a 7-mm-thick human skull, using outputs ranging from 570 to 635 joules. The 89-mm-focal-length lens was used, except once when the 53-mm lens was employed. The effect of having the focal point on the surface, as well as deep to it, was tested. Exposed Polaroid film was placed within the skull in close contact with the part of the skull to be struck with the laser. In all instances but one, there was no light effect on the Polaroid film, indicating less than 0.71 joule's transmission. In the one instance in which the 53-mm focal length was used, a faint blanching of the film was noted, indicating less than 10 joules' transmission.

More light transmission was seen when similar tests were done on skin from a young dairy goat. This skin was 1.2 to 1.6 mm thick. The 33-mm-focal-length lens was used in some tests, but most were done with the 89-mm lens. A maximum output of 735 joules was used, the maximum total spot size being 1.42 cm when focused. The light transmission was tested by a calorimeter placed behind the skin and, in some instances, by exposed Polaroid film placed against the back surface of the skin. The calorimeter detected less than 0.1 joule on some of the shots. The maximum light transmission recorded was 26 joules through a 1-cm orifice, or 34 joules/sq cm. The higher levels were obtained later in the series, when the skin was possibly somewhat drier. It is possible that the readings also included light from the "plume." In none of these was there evidence of gross damage to the underside of the target.

Light, in itself of short duration and low intensity, does not produce gross injury. Therefore, the next consideration is of the parameters of laser beams that might be injurious.

## III. THERMAL EFFECTS.

The most important factor to consider is heat. When light strikes a target, its energy is liberated in the form of heat.

In evaluating the potential damage from heat, several factors must be considered. The first is the amount of heat necessary to produce damage. This depends on the target material and the duration of exposure. Damage to a nonbiological target is influenced by factors such as the ignition, melting, or boiling points of the material and its color and reflectivity. In nonbiological targets, structural characteristics, such as ductility and the tendency to crack from expansion, also influence the onset of damage from heat. In living material, there is built-in protection from thermal injury because of the high proportion of water in most tissues. Striated muscle is about 75% water, skin about 70%, connective tissue (chiefly collagen) about 60%, fat about 20%, brain about 85% (gray matter) or 70% (white matter), and liver about 70%.[7] The high thermal capacity of water, using about 4 joules (1 cal) to raise 1 gm of water 1°C, means that to raise the temperature of water from 37° to 100°C, approximately 252 joules/gm would be required. To change 1 gm of water to 1 gm of steam at 100°C, 2,160 joules (540 cal) is required.

In studies on young pigs, Morton and coworkers found that in a 1-sec exposure, 5.5 cal/sq cm was required to produce a burn greater than simple erythema, which was produced by 3 cal/sq cm.[8] Sherman has produced reproducible second-degree burns of human volunteers by a hot-air exposure of 8 cal/sq cm for 2 sec.[9] Thus, if sufficient energy density is delivered for a sufficiently long time, one can expect that there will indeed be a burn, or, with higher energy, actual vaporization of tissue at the surface of the skin. If the tissue is semitransparent, so that focus deep to the surface is obtained, one can expect that the maximum effect may be a short distance beneath the skin. Once the energy has been used in producing the tissue reaction, however, the residual energy density is much reduced, so that there should be progressively less damage as the beam extends deeper into fairly homogenous tissue. If there is a localized area of unusually great absorption, such as a spot of black pigment, more thermal effect would be seen at this point, with relatively less deep to it. In the skull shots described previously, when about 700 joules was focused either on the surface of a human skull or deep to the surface, holes about 4 mm in depth resulted, without penetration of the skull, which was 7 mm thick. The surface was then painted black, and it was again struck with the focused 2-msec beam. A much more intense surface reaction was seen, but the depth was not measurably altered (figure A3). The residual energy was still great enough to produce the characteristic localized area of destruction.

The rate of delivery of energy is important in determining the depth of the damage. If, as in the use of these pulsed lasers, the application of heat is for so brief a time (1 to 2 msec) that conduction into the tissue cannot occur, all of the nonreflected heat remains at the surface, producing a perhaps more intense effect, such as vaporization of the tissue, if it is hot enough. The shorter the duration of exposure to heat, the more localized the effect, because it requires a finite time for heat to penetrate tissues by conduction. With relatively low amounts of heat applied over a fairly long time, the amount of damage bears some relationship to the amount of heat and its duration, but at the extremes this does not apply, forming an asymptotic curve.[10-12] Thus, at the lower extreme of the curve, when an amount of heat just above the threshold needed to produce any burn at all is applied for progressively longer times, there is not as much change in the amount of damage with increasing duration as there would be for a higher-temperature application to the skin for shorter periods of time. Similarly, when very high temperatures are applied to the skin for very short periods of time, there is relatively little difference between the severity of the burn at one very high temperature compared with another at a different very high temperature. With very short durations of exposure, one cannot expect thermal damage to occur deep to the skin because there is inadequate time for conduction[13,14] (figures A5 and A6).

One group of investigators[15] has reported greater damage to small animals from the short-pulse (less than 10 nanoseconds) laser radiation compared to a long-pulse (1 msec) laser radiation. The long pulse used, however, had a 7- to 10-joule output and was compared to a short-pulse, 3-joule output. The 7- to 10-joule output is so low that it is close to the energy output of the short pulse. The differences observed possibly can be attributed to a greater efficiency of energy delivery with the "Q-spoil" in their studies, so that the central portion of the target actually received a higher energy density than with the long pulse. Small differences in distances and lens systems and other factors could contribute to this effect. Our comparative studies differed in that the total energy delivered by the short pulse (about 3 joules maximum) was very much less than that delivered by the long pulse (over 100 joules), but the maximum peak power of the short pulse ($10^7$ w) was approximately three orders of magnitude greater than that with the long pulse. This discrepancy had the effect of separating pressure effects, which were more marked with the short pulse, from thermal effects, which were much more marked with the long pulse in our studies.

The pathological effect of the laser on tissues should not be considered unique, unless it can be definitely proven to be so. A laser burn can be considered a sharply localized flash burn. Much work on flash burns has been done since the advent of thermonuclear weapons. The following statement,[4] which concerns thermal effects from nuclear weapons, could be applicable to the effects of the long-pulse (1 or 2 msec) laser:

> ...a given amount of energy may be less effective if delivered in a very short pulse, e. g., a fraction of a second, than in one of moderate duration, e.g., one or two seconds. In some experiments in which certain materials were exposed to short pulses of thermal radiation, it was observed that the surfaces were rapidly degraded and vaporized. It appeared as if the surface had been "exploded" off the material, leaving the remainder with very little sign of damage. The thermal energy incident upon the material was apparently dissipated in the kinetic energy of the "exploding" surface molecules before the radiation could penetrate into the depth of the material. ...the majority of flash burns show a much smaller depth of penetration than do flame burns.

The sharp localization and demarcation of flash burns of skin, with relatively complete destruction in the small depth involved, has been noted by several investigators in human and experimental studies.[8,11,12,16] These effects are very similar to those noted here with the high-energy, long-pulse laser (figure A4).

One group of investigators has noted, in small animals, "normal, intact tissues intervening between the superficial and deeper lesions," and concludes that these "exclude purely thermal causes."[15] Assuming that the word "thermal" is used to mean an effect resulting from the delivery of energy in the form of heat into the tissue, this conclusion may not be valid. It would not be unexpected to find variation in damage from thermal effects when the laser radiation passes through varying types of tissue that have differing absorptive characteristics. Also, it is possible, in translucent tissues, to have the focus deep to the surface, in which case, the maximum effect will be at the site of maximum energy density, which, then, can be deep to the surface. When, in small animals, a plume is produced within the tissues, the trauma from this jet of vapor would be more noticeable in more easily contused tissues than in others which might be less vascular or more freely movable.

When the laser is applied to the skin, liver, or lung of small animals, circumscribed, conical holes, each with a narrow rim of coagulation, result. Similar effects can be obtained with the high-frequency current used in electrosurgical apparatus (for instance, "Bovie," figure A6). The high-frequency current is not a cautery; it produces its effect by heating of the tissues from resistance to the passage of an electrical current. The effect of the 1- to 2-msec laser pulse is best simulated by applying the undamped "cutting" current through a round-tipped electrode of the type usually employed with the spark-gap or "coagulating" current. This is not the way in which the electrodes are used clinically. Thorough studies were not made to determine whether the two mechanisms of tissue destruction are identical, especially as it is difficult to determine the amount of energy per unit time produced by the "Bovie." This simple comparison was made only to illustrate that the laser should not be considered to be the only way of producing a given result. If there is an indication of producing localized tissue destruction, another modality, such as the electrosurgical apparatus, should be tested, both for elucidation of the mechanism of action and because these other modalities are cheaper, safer, more controllable, and already available. One can fairly well predict the diameter of a laser "lesion" and the amount of energy delivered, but there is no real control of the depth of the lesions in tissue, except the knowledge that it will not exceed a few millimeters in solid tissue. With skillful use of the electrosurgical apparatus, selecting the correct electrodes and currents for the purpose, one can vary the size, shape, and depth of a wound to meet the needs of a given situation. The degree of hemostatic effect can also be varied depending on the length of time the electrode is held in contact with the tissue and the type of current used. Some have reported use of the laser, not so much for immediate excision or destruction of a portion of tissue with a certain degree of hemostasis, but, rather, to produce later fibrosis in a fairly localized area.[17,18] Improved radiation techniques, including local implantations of radioactive materials with short half lives and other sources of electromagnetic radiation in the infrared, visible, ultraviolet, and other frequencies should be considered and compared before the laser is considered to have a unique effect or to be the optimum method of achieving these results.

The thermal effects of potential harm, from the standpoint of acute injury, can be divided into two groups.

A. Coagulation of the Protein of the Tissue.

Heat produced by the laser causes coagulation of tissue protein, as in any burn, thus, damaging or killing the portion involved.

B. Vaporization.

Vaporization removes the central portion of the target. In tissue, it leaves a hole not exceeding about 2 mm in diameter, whether about 700 joules is placed in a 4.8-mm-diameter spot size (which is the highest energy density we achieved) or, using other lenses, in up to 20-mm total spot size. This little hole is not a significant wound to the skin of man or even to the skin of a small animal. With its halo of coagulation necrosis, this could be harmful to structures such as bowel or blood vessels, but, because of the thickness of the body wall in man and large animals, this cannot occur unless the bowel or vessel is exposed surgically or if, for some reason, the overlying skin and subcutaneous tissue is less than 5 mm thick. The maximum depth of the crater we have been able to obtain, using various tissues from various species, does not exceed 4 mm and is usually much less. On microscopic examination of the skin lesions, the maximum depth of the crater was about 3 mm, and the maximum depth of any effect, using excised skin or intact anesthetized animals, was 3.5 mm. These deeper effects are as seen on histological examination and include necrosis of collagen and elastic fibers and leukocytic infiltration, consisting mainly of round cells, noted a week later in the intact animal.

Because of the very rapid, intense heating, a jet of vaporized tissue is produced. On the surface, this is dissipated into the air in the form of a plume, and does not significantly traumatize the tissue, except in the very immediate periphery. The resulting pressure alterations peripheral to the vaporized portion can be seen, on high-speed photography, as rapidly attenuated, ripplelike, radiating waves. When a plume occurs in a confined space, it can be predicted to produce pressure effects similar to those from a small jet of compressed air. This can produce serious damage in the eye and can injure other parts of thin-walled, translucent animals where, besides direct heat injury, effects resembling contusions have been seen[15, 19-21].

that could be attributed to this source. The most serious result, studied by Hayes and coworkers,* occurs in the brain of the small animal, where displacement of the structures within the calvarium can occur,[1] probably because of the rapidly expanding gases. The thickness of the skull of large animals and man, however, prevents the penetration of sufficient laser energy to produce these effects. When 480 joules was focused in a total spot size of 1.42-cm diameter on the clipped scalp of an anesthetized rabbit, the plume was superficial, and the animal behaved normally after recovery from the anesthetic. When it was sacrificed and autopsied 1 wk later, a localized lesion, extending through the scalp and calvarium into the brain, was seen (figures A5 to A8). This was not unexpected because the scalp was only 1 mm thick and the skull, 1 mm thick. The microscopic examination of the lesion in the brain (figures A9 and A10) was summarized by the pathologist as follows:

> The lesion produced by the laser involves adjacent portions of the right and left cerebral hemisphere. The lesions are similar in both the right and left sides, being triangular in shape with the base at the meninges and the apex in the underlying white matter. In the center of the lesions there is a defect, evident even in the gross, measuring 2.5 mm in width and 1.5 mm in depth. The superficial cortex about the defect is completely necrotic and filled with large mononuclear phagocytic cells and proliferating vessels measuring 6 mm in width. Beneath the defect there is a zone of eosinophilic necrosis measuring 6 mm in width and 5 mm in depth where only the vascular elements appeared to have survived. This zone of eosinophilic necrosis contains varying degrees of hemorrhage depending upon the section. Surrounding the zone of eosinophilic necrosis is a reactive zone. Some of the neurons in this zone show necrobiotic changes. The astrocytes are generally hypertrophied, the microglia appears activated, and the vessels show proliferative changes. This zone of reaction also shows hemorrhages which are predominantly limited to the region about vessels.
> Comment: The morphological alterations are generally not unique except for the presence of a prominent permanent defect, possibly representing vaporization of

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* Hayes, J. R., Fox, J. L., and Stein, M. N. The Effects of Laser Radiation on Brain Tissue. I. Preliminary Studies. (In preparation).

tissue, in the central and superficial portions. Many of the changes resemble findings in lesions produced by blunt trauma or experimental localized freezing of the brain.

Some investigators have commented upon the fact that skin lesions observed after laser "impact" show fibrosis and other cellular changes extending beyond the spot "struck" by the laser beam, and some have considered this to signify an unusual effect peculiar to laser action. There are some very simple possible explanations for these observations, which should be considered before the more esoteric theories. First, it is difficult to know the exact diameter and depth of tissue illuminated by the laser. The spot size is usually predicted by use of a non-laser light source and can be tested by use of exposed Polaroid film, which, however, cannot be used at the same time as the skin exposure. When the laser radiation is applied to the tissue, as can be seen in high-speed motion pictures, there is considerable spread within the area illuminated in a translucent target, such as tissue. Also, because the central portion of the laser beam (whether focused or unfocused) tends to have a higher energy density than the edges, an amount of laser energy sufficient to remove a central portion of tissue will have around it concentric circles of decreasing density marked by coagulation (if the time of exposure was long enough and the energy high enough), progressing peripherally to areas of cellular damage insufficient to produce immediately apparent necrosis. The presence of such peripheral areas may account for the occasional subsequent thrombosis of small blood vessels and regression of incompletely destroyed tumors noted by McGuff.[22] If the central portion of the tissue has been vaporized, there is also contusion of the immediately adjacent tissue by the sharply limited pressure effects. This can be observed on high-speed motion pictures and measured with appropriate pressure sensors. All of these effects occur within a very small volume of tissue, so that they are of interest, for instance, to those attempting to destroy or damage small, superficial lesions of skin, but they are not of concern as acute surgical problems.

## IV. PRESSURE WAVES.

The last point to consider is the formation of pressure waves from the action of the laser itself (as opposed to the action of the expanding gases of the plume). When the 1- or 2-msec pulse is used, although a shock wave occurs at the point of impact, the pressure after passage through only a few millimeters of tissue is so small that it is hard to find a sensitive enough detector. The pressure was measured at less than 10 psi, and, as the surface involved was much less than a square inch, the actual pressure was considerably less. To obtain a measurable pressure wave, it is necessary to use the high peak power of the "Q-spoil" laser pulse. This pulse has a duration of about 15 to 25 nanoseconds, compared to the 1 to 2 msec of the long pulse, and results in measurable pressure waves, even though the total energy output is much less, and practically no gross effect is seen on the tissue. In our studies, the pressures were measured with a transducer with a 0.1-μsec rise time.[23] When the high-peak-power laser beam strikes a surface, resulting in vaporization of material at the point of contact, the ejection of the vaporized material gives a propulsive effect to the tissue behind it. The action exceeds the speed of sound, producing a shock wave at the point of impact. The force of this wave, however, decreases very rapidly as it passes through tissue. This, too, can be predicted on the basis of known physical principles, although the precise action depends on factors such as reflection from interfaces, and one can very roughly estimate the reduction in force of a pressure wave by the inverse-square law. Thus, 1,000 psi striking 1 cu mm of tissue could be 1.5 psi 1/2 in. (13 mm) away and 0.4 psi 1 in. away.

The effect of the pressure wave is attenuated not only by passage through a medium, but also by the ductility of the tissue. The soft tissues of the mammalian body are exceedingly resilient, acting as very efficient shock absorbers. Our previous studies with pressure transducers placed behind varying thicknesses of tissue, as well as with tissue placed over water (to simulate a solid viscus) and over a small air-filled balloon (to simulate a gas-filled viscus), revealed that after the passage of a few millimeters through tissue and a little over 1 in. through the air and water, the resulting pressures in the small areas involved were far below those capable of inflicting injury elsewhere than the eye. When an almost transparent medium, a small block of 20% gelatin, was substituted for the tissue, the light went through the gelatin, and a pressure pulse of over 2,000 psi was immediately recorded by the transducer.[24] This suggests that there may, indeed, be significant pressure waves produced in the eye but not after passage through less transparent tissue.

The pressure effect of the laser is infinitesimal compared with the forces from, for example, a land mine which may impart about 566,000 psi in 3.5 μsec.[25] This can blow off a man's lower extremities, but, aside from the effects of the fragmentation of the mine, relatively little remote effect due to transmitted pressure is seen. A cal .45 bullet imparts about 494 joules into the tissues and a military rifle bullet about 3,600 joules. Bullets impart tremendous forces to the tissues they fling apart, but there has been no proven "pressure wave" damage to tissues or organs outside this temporary cavity.

## V. CONCLUSIONS.

In conclusion, except for the eyes, from a surgical standpoint, there is no reason to expect other than superficial damage from accidental exposure of man or large animals to lasers. Experimental data tend to confirm the theoretical principles involved.

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## APPENDIX

## FIGURES

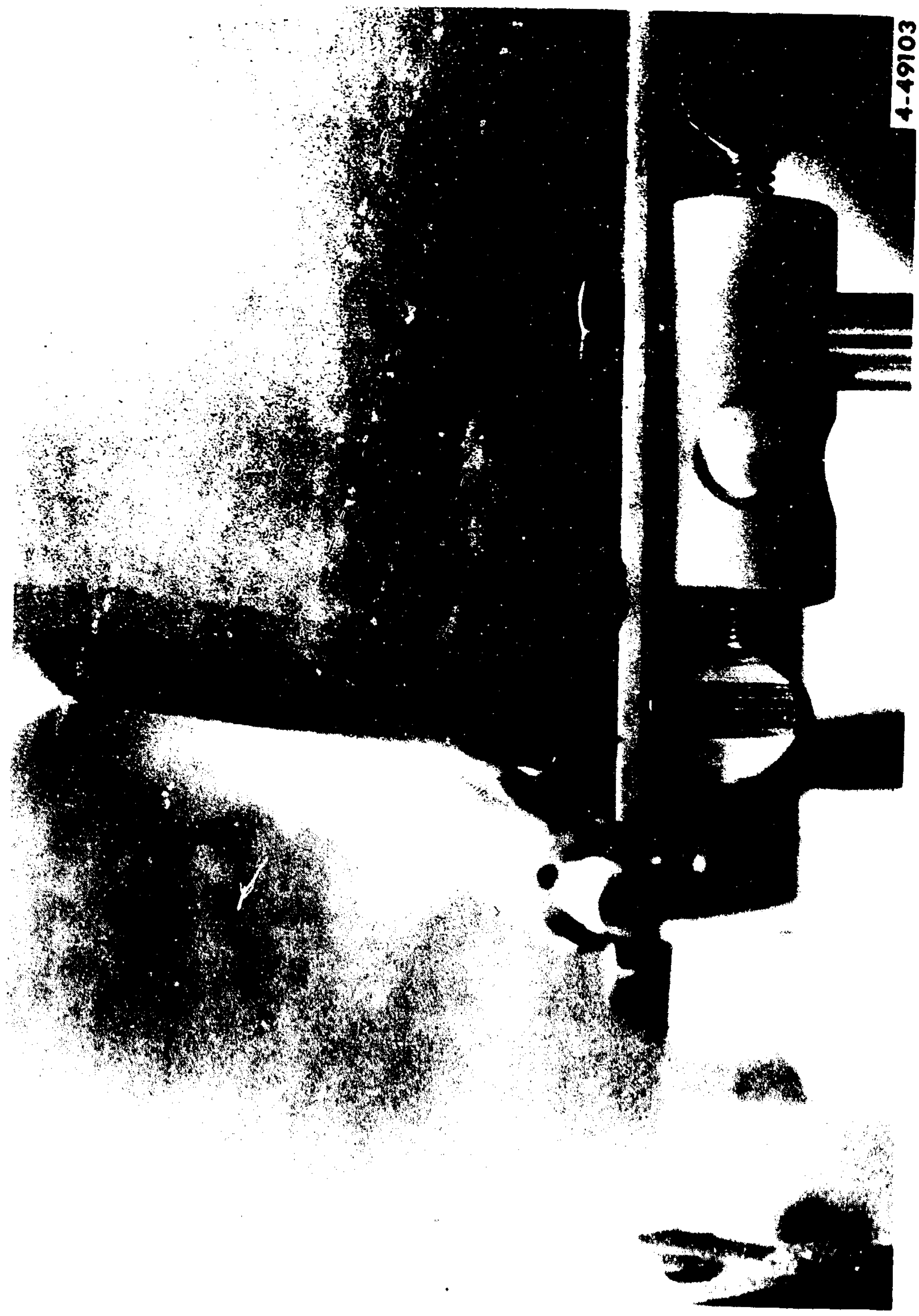



Figure A1. Laser Beam Focused on Surface Bakelite Target

**(Pressure gage is mounted at right angles to target; previously published in Federation Proc. Suppl. 14, January-February 1965; reproduced by permission)**

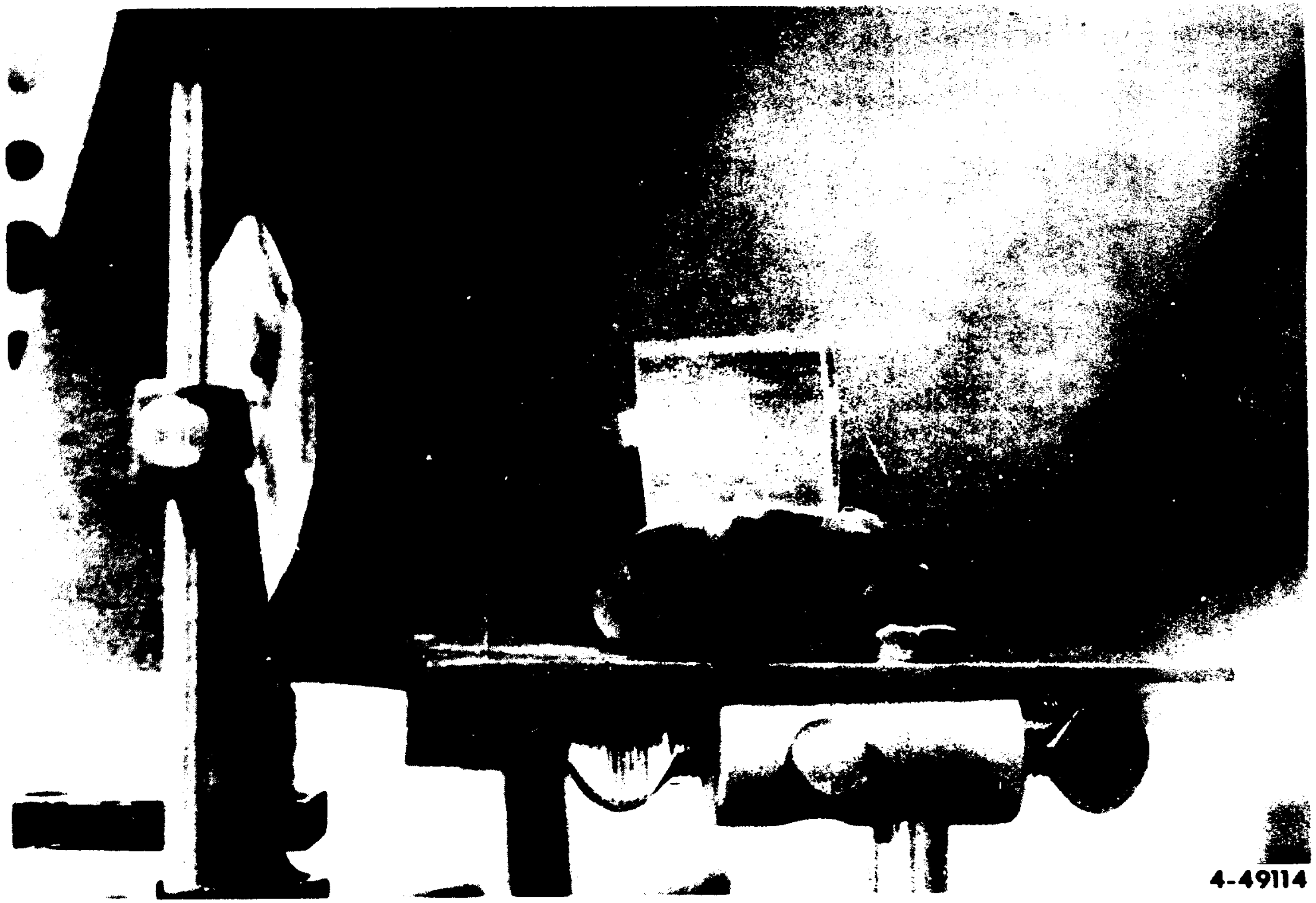
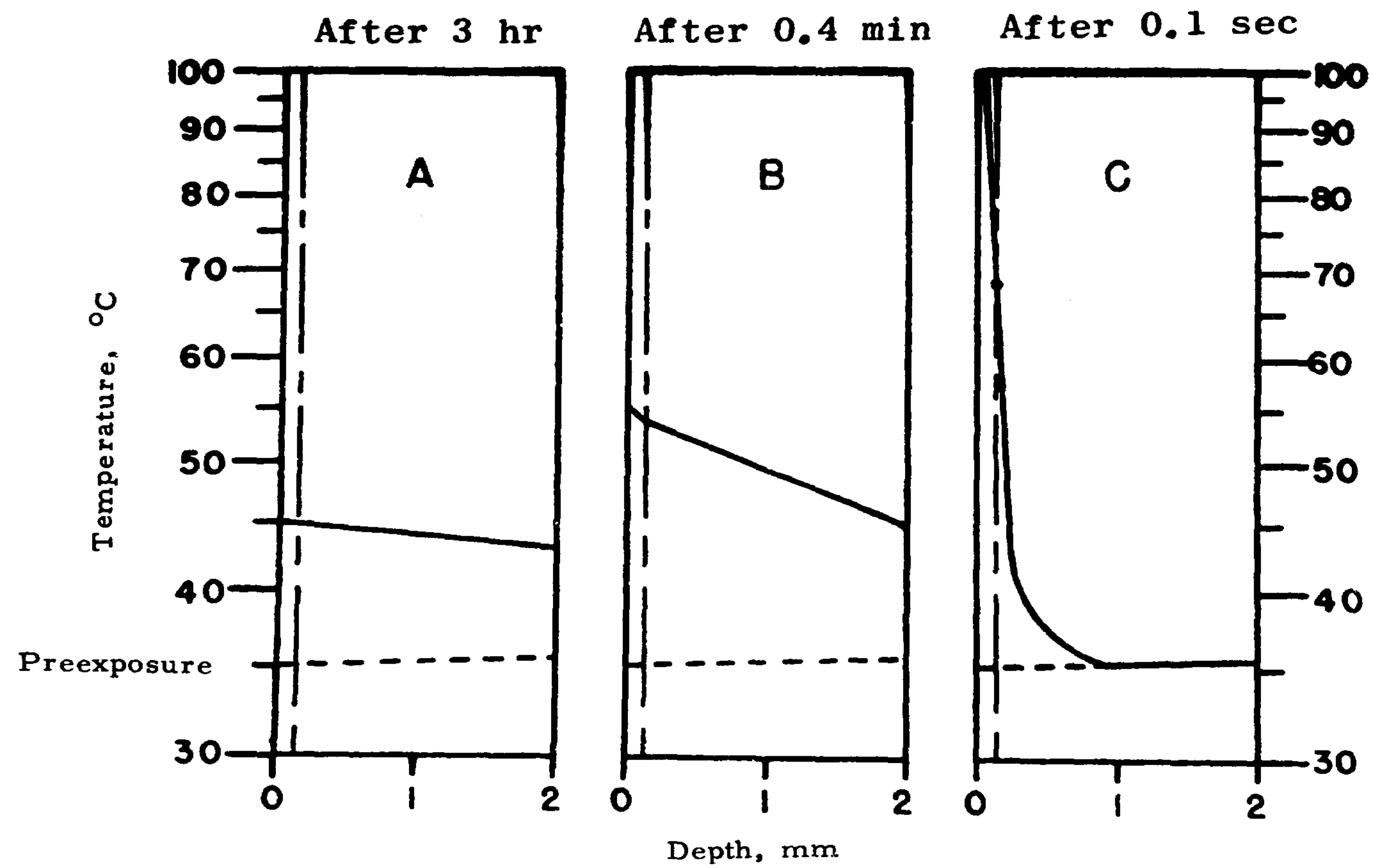



**Figure A2.** Laser Action Penetrating Into Block of Lucite

**(Previously published in Federation Proc. Suppl. 14, January-February 1965; reproduced by permission)**




4-57943

Figure A3. Effect of Temperature and Duration on Depth of Tissue Heating

[Temperature gradients after exposure just producing epidermal necrosis (After Moritz)]

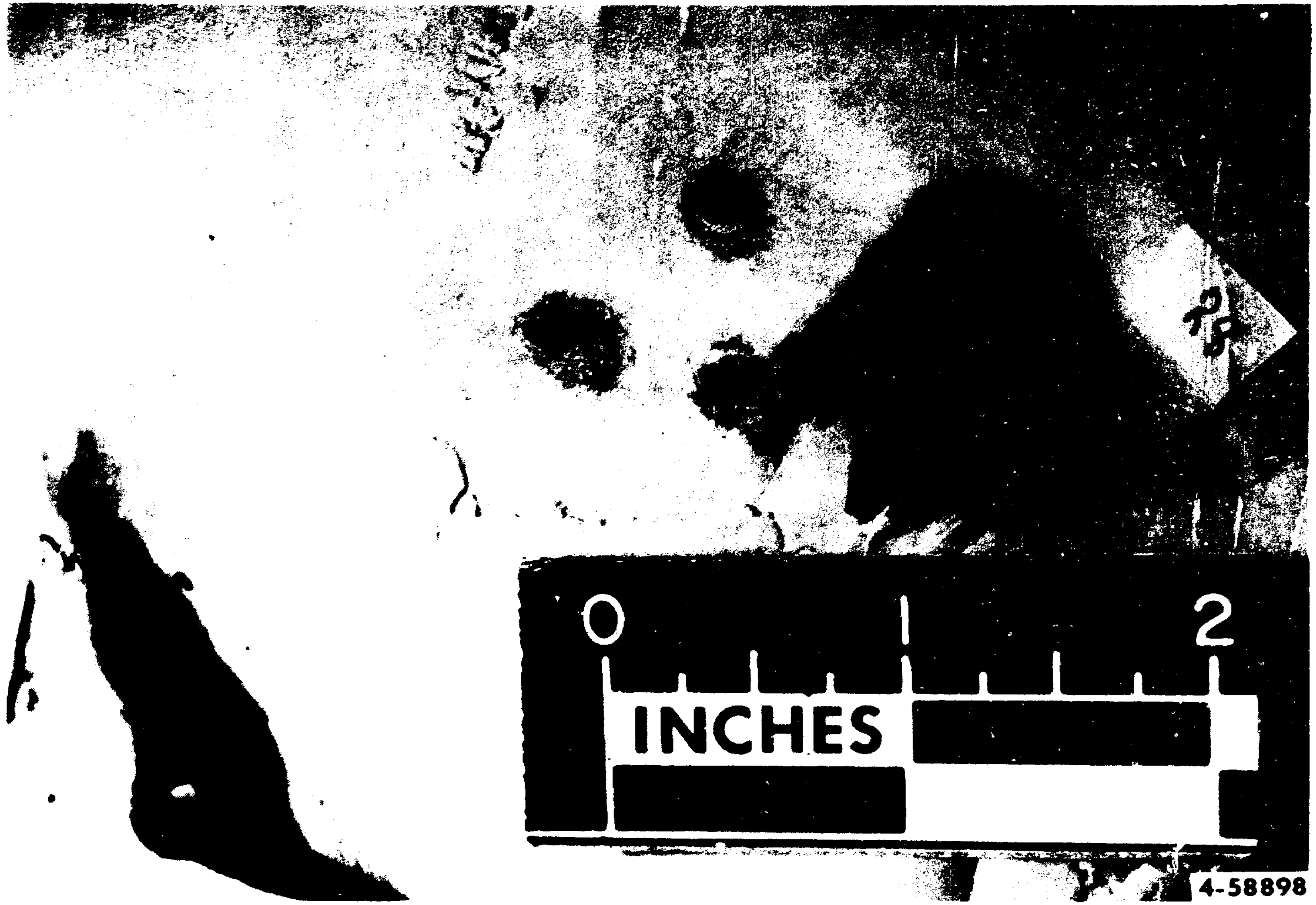


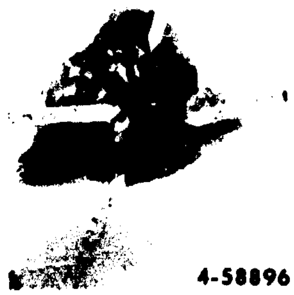

**Figure A4.** Human Skull Following Laser Radiation Under Varying Focusing Conditions

(Large black area around shot No. 28 is ink; no ink was used on other shots)

4-58533

Figure A5. Goat Skin That Received 735 Joules in 2 Msec (1.42 Cm Total Spot Size)

[Note sharp demarcation of laser effect on left side of field, limited to epidermis and dermis (H&E X31)]




A


B


C

Figure A6. High-Frequency-Current Lesions Resembling Those From High-Energy Lasers

A. Defects produced in rabbit lung by electrosurgical apparatus ("Bovie") and by laser delivering about 700 joules

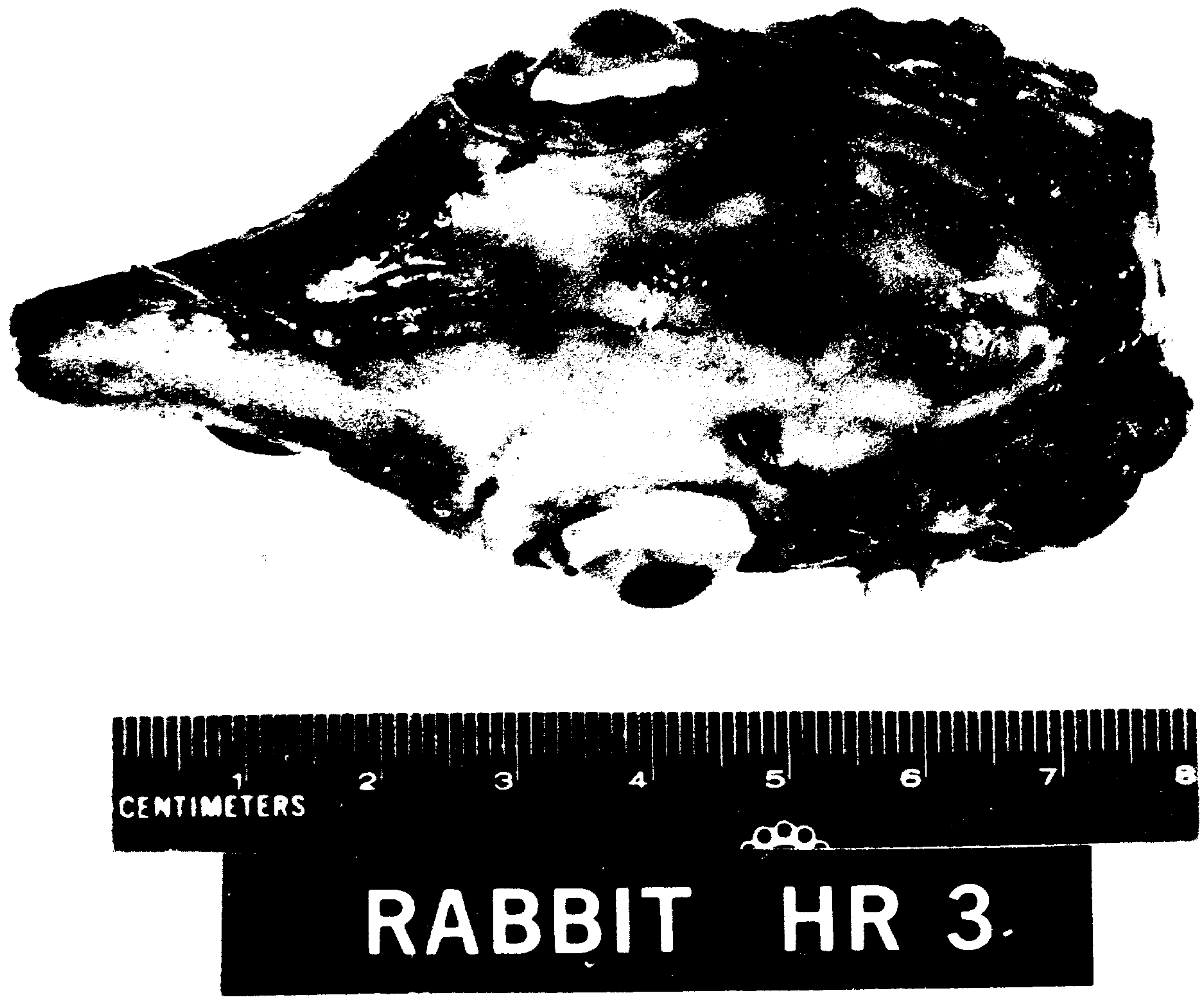
B. Rabbit skin on which 140 joules from laser has been focused in about 1-mm spot size (H&E X31)

C. Rabbit skin touched with "Bovie" needle for 1.05 sec with cutting current at power setting "45" (H&E X31); note central defect and sharply demarcated tissue alteration limited to superficial portion of dermis in both B and C.


4-56367

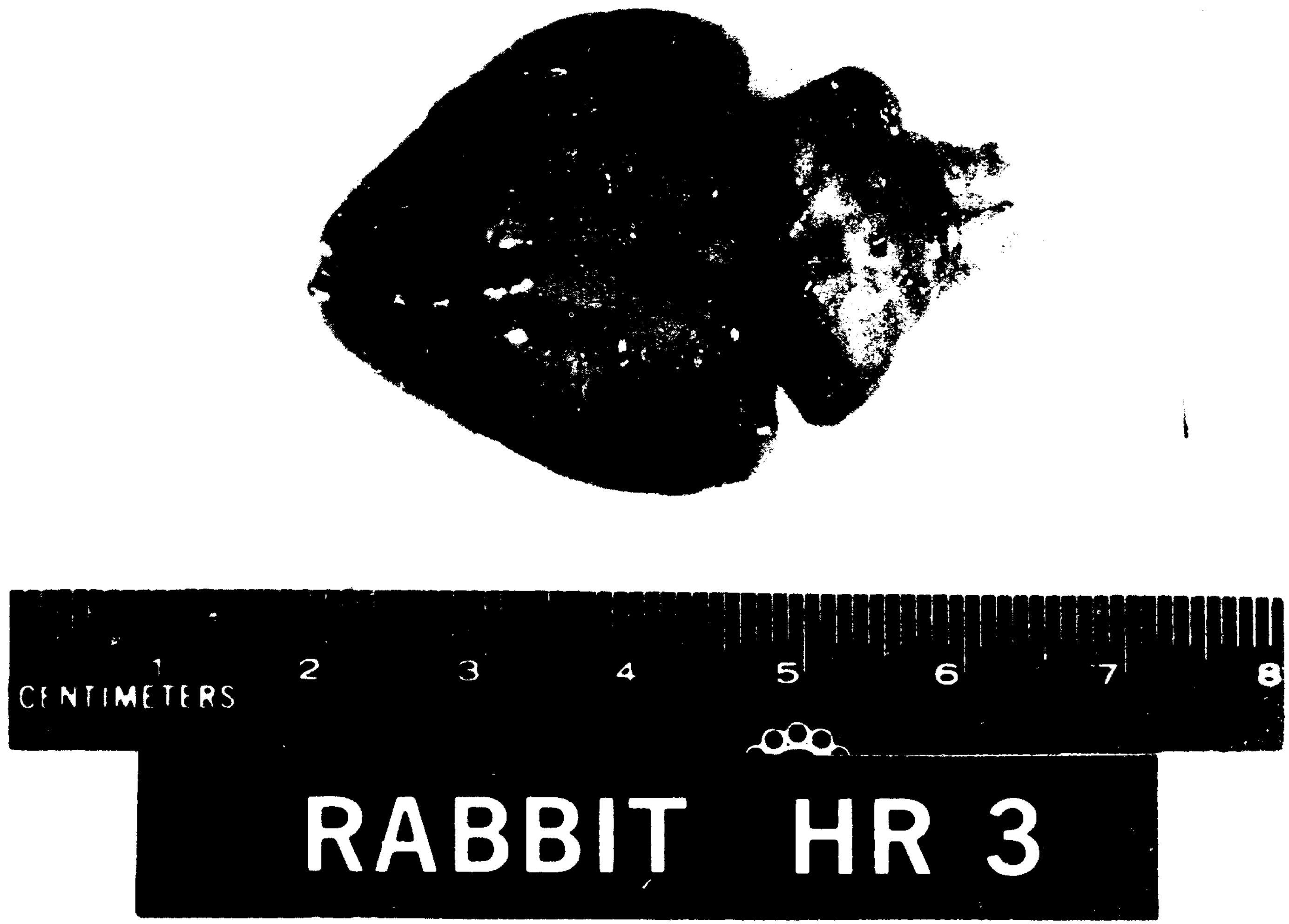
Figure A7. Scalp Wound of Rabbit 1 Wk After 740 Joules Laser Irradiation

(Same animal is used in figures A7 to A12)



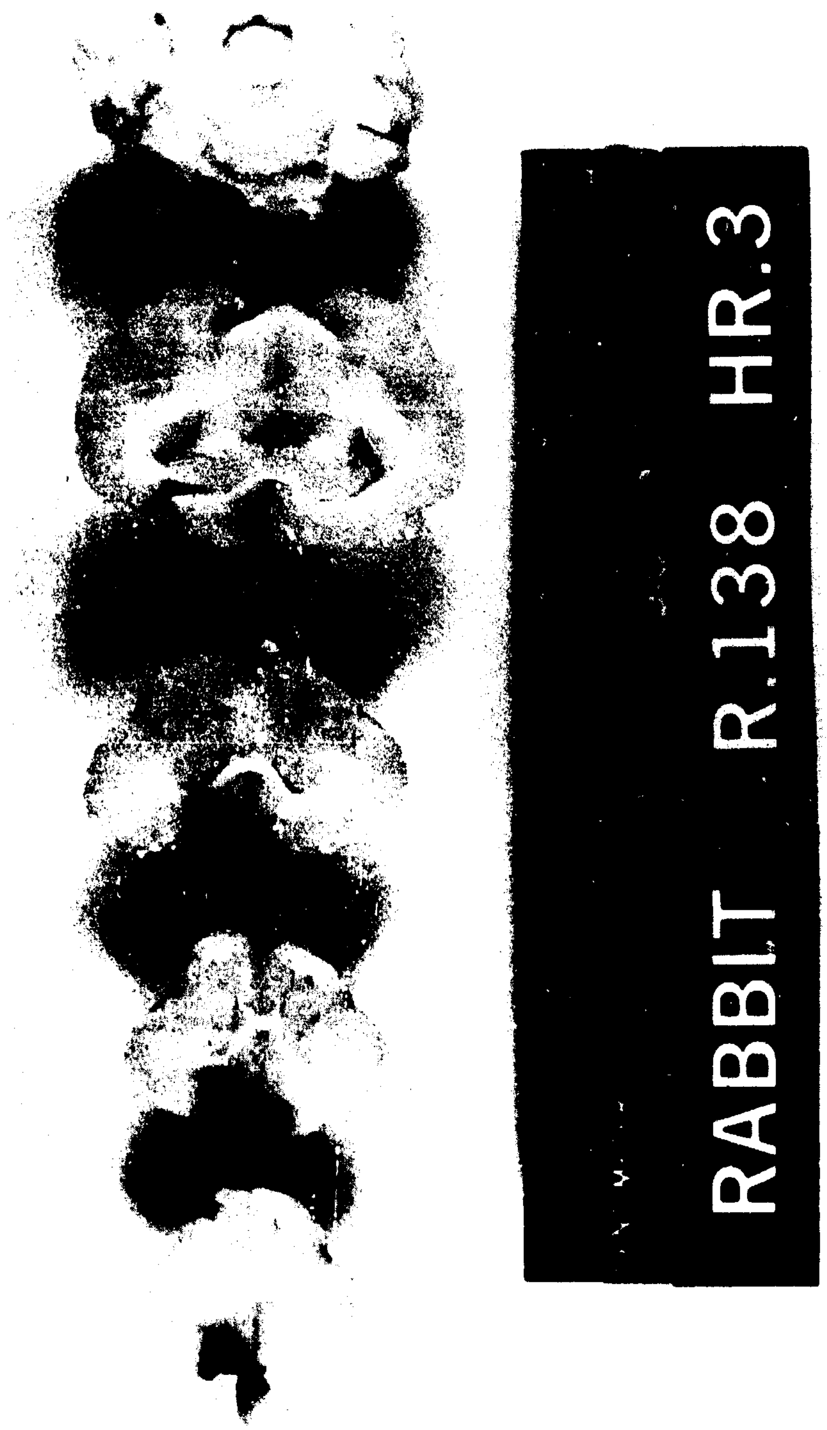

4-56369

Figure A8. Periosteal Hemorrhage in Calvarium Underlying Scalp Lesion




4-56368

Figure A9. Lesion in Right and Left Frontal Lobes Underlying Calvarium




4-57499

Figure A10. Coronal Sections of Rabbit Brain Showing Hole and Adjacent Hemorrhage


Figure A11. Section of Right Frontal Lobe Showing Hole, Limited Necrosis, and Marginal Reactive Zone (H&E ×31)


Figure A12. Section of Left Frontal Lobe Showing Necrosis With Hemorrhage Capped by Necrotic Cortex Filled With Macrophages (H&E X31)

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13. ABSTRACT
The purpose of these studies was to determine whether there is any significant hazard to man accidentally exposed to a laser beam striking elsewhere than the eyes. This work concerns acute injury, of surgical significance, without consideration of long-term effects. The maximum energy density tested was about 700 joules/2 milliseconds in a .48 cm spot size, obtained with a neodymium-doped glass laser rod. A "Q-spoil" laser delivering about 3 joules with about $10^7$ watts maximum peak power were also used. Both "thermal" and "pressure" effects were tested, the former being more marked in the "long-pulse" mode and the later in the short-pulse. As can be predicted from known physical principles, despite intense effects at the point of "impact," all of these are so rapidly attenuated on passage through tissue that, except possibly in the eye, no surgically significant damage to intact large animals or man should be expected following accidental exposure to laser.

14. KEYWORDS

| | |
|---|---|
| Laser | Thermal effects |
| Trauma | Pressure effects |
| Tissue | Shock waves |
| Physical effects | Penetrability of laser |
| Injury | |