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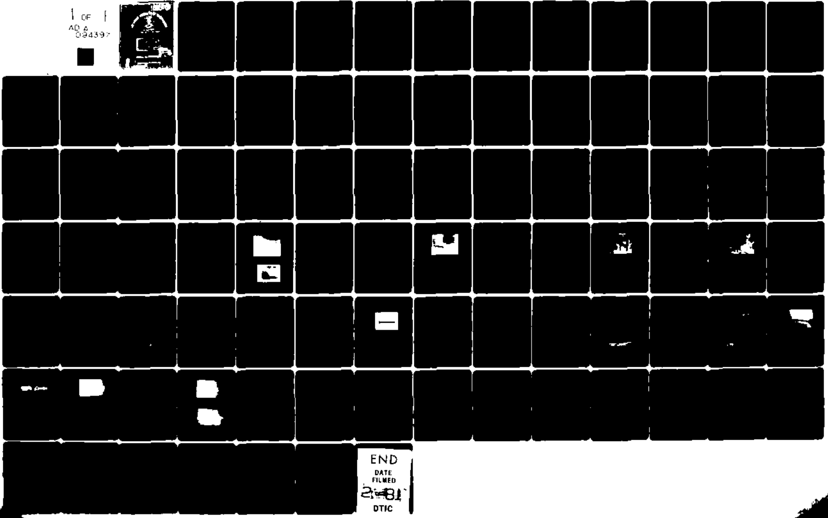

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A CO_2 LASER SYSTEM FOR CORNEAL SURGERY

Master's THESIS

(14) AFIT/GEP/PH/80-6

WILLIAM ~~H.~~ Harold POSSEL
~~Lt~~ USAF

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A CO_2 LASER SYSTEM FOR CORNEAL SURGERY

THESIS

PRESENTED TO THE FACULTY OF THE SCHOOL OF ENGINEERING
OF THE AIR FORCE INSTITUTE OF TECHNOLOGY
AIR UNIVERSITY (ATC)
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

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BY
WILLIAM H. POSSEL, B.S.
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DECEMBER 1980

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Preface

Until now, no one has attempted to use the CO_2 laser as a "scalpel" in corneal surgery. This thesis demonstrates that it is possible for a CO_2 laser to make corneal incisions of controlled width and depth such that the laser may someday replace the scalpel in many surgical procedures.

I wish to express my sincere appreciation to Professor Leno S. Pedrotti, my thesis advisor, who guided me in this project. I am indebted not only for his critical comments and stimulating discussions but also for the painstaking care he took in reading earlier drafts of this thesis. I would also like to thank Dr. Richard H. Keates of the Ohio State University Eye Clinic for sharing his knowledge and resources. Thanks are also due to Lieutenant Colonel Hugo Weichel for his helpful suggestions and criticisms.

Messrs. James Miskimen and Ron Gabriel, the physics laboratory technicians at the Air Force Institute of Technology, helped me tremendously with their technical expertise and assistance. Thanks go to Mrs. Roz Holland, Dr. Keates' assistant, for her aid with the corneal tissue and for the photographs she took of the histological sections. I would also like to express my appreciation to Ms. Dorothy Smith for expertly typing the final draft of the thesis.

Finally, I wish to thank my wife, Marie, not only for editing and typing the rough draft but also for her patience and understanding throughout this entire project.

Table of Contents

List of Figures

Figure Page

List of Tables

List of Symbols

Θ_f	Half-angle beam divergence of the expanded beam (radians)
Θ_i	Half-angle beam divergence of the incidence beam (radians)
λ	Wavelength of the laser (microns)
A	Cross sectional area of laser beam (cm^3)
C	Heat capacity of cornea (cal/g-^oC)
d	Depth of corneal incision (microns)
D_f	Diameter of expanded beam (m)
D_i	Diameter of incident beam (m)
E	Energy of laser (J)
f	Focal length of focusing lens (mm)
f_1	Focal length of negative beam expander lens (mm)
f_2	Focal length of positive beam expander lens (mm)
L	Latent heat of transformation of cornea (cal/g)
p	Density of the cornea (g/cm^3)
P	Output power of laser (W)
Δt	Pulse duration of laser (sec)
T	Normal corneal temperature (^oC)
T_v	Boiling temperature of cornea (^oC)
V	Volume of vaporized cornea (cm^3)
W_{01}	Beam waist radius of laser beam incident on focusing lens (mm)

W_{02}	Beam waist radius of laser beam after focusing (mm)
$W(Z)$	Spot size at a distance Z from the focal plane (mm)
Z_1	Distance from beam waist of the incident beam to focusing lens (m)
Z_2	Distance from focusing lens to focal plane (mm)
Z_R	Rayleigh range (microns)

ABSTRACT

A CO_2 laser optical system capable of precise control of output power, beam divergence, and spot size was designed to investigate cutting properties of the focused laser beam on corneal tissue. The laser system was tested in three different modes of operation: continuous wave (CW), externally chopped, and Q-switched.

In order to obtain preliminary measurements on the spot size of the focused beam, thermal copying paper was used. The smallest beam diameter measured on this paper was 25μm. Clear plastic sheets were employed to give an indication of what to expect in a corneal incision. Precise beam control was demonstrated by rupturing a 9-0 Ethicon suture with an energy as low as 0.75mJ. Bovine and hog corneas (obtained from a local abattoir) were utilized as more realistic targets for tests of laser beam control. Finally, one human eye-bank eye that had been rejected as donor material was used as a target.

The results indicate that the CO_2 laser can make corneal incisions with a controllable penetration depth of 10μm and deeper and a width as small as 50μm. With such accurate control, the laser may supplement and even replace the scalpel in some surgical procedures. These procedures

include, for example, radial keratotomy, epikeratophakia, relaxing incisions following corneal transplants, and rapid and precise cutting of surface sutures. By integrating a CO_2 laser system with a standard slit lamp, the ophthalmologist should have a safe and useful tool in laser surgery of the cornea.

A CO_2 LASER SYSTEM FOR CORNEAL SURGERY

I Introduction

The use of lasers in medicine and the confidence of the medical community in lasers are both increasing. Lasers have been used as surgical tools in many medical fields including ophthalmology, otolaryngology, gynecology, dermatology, and plastic surgery. In ophthalmology, lasers have already been employed successfully in the treatment of retinal detachments, vascular abnormalities, and both angle-closure and open-angle glaucoma. To date, so far as known, the laser has not been used as a "scalpel" for controlled cutting or shaping of the cornea. If the width and depth of the laser incisions on corneal tissue can be controlled, it is apparent that the laser may be useful in surgical applications associated with the cornea. A particular application is radial keratotomy. This surgical procedure is designed to correct myopia without the use of glasses. If a properly designed CO_2 laser system can be successfully used in radial keratotomy, the United States Air Force may be the beneficiary of a substantially larger pool of pilot candidates.

Objective and Scope

Since the cornea is essentially opaque to infrared radiation at 10.6 μm, the carbon dioxide laser is a natural system to exploit for application as a precise laser knife. The problem in this study is to design a CO_2 laser optical system capable of precise control of output power, beam divergence, and spot size. The system is then to be tested on two different types of calibration materials (thermal copying paper and plastic sheets), on surgical sutures, and finally on both animal and human corneal tissue. The laser is evaluated in three different modes of operation; continuous wave (CW), externally chopped, and Q-switched. Earlier studies (Ref 1:76; 2:266) indicate that the rapid super-pulsed mode (pulsed electric discharges) is superior to the CW mode when cutting tissue other than the cornea because there is less charring and puckering of the tissue.

This experiment does not include a definitive study on thermal conduction and local temperature changes in the cornea following laser irradiation of the cornea, or the design of an integrated system which satisfies the man/machine (surgeon/laser) interface requirements. It is necessary to conduct an investigation of possible thermal damage to the endothelium layer of the cornea before the ophthalmologist begins using the laser on living human eyes.

Development

In Chapter II, a historical survey on lasers in ophthalmology is presented. Included in this chapter is a description of the eye and cornea, and the potential applications in corneal surgery of a CO_2 laser system integrated with a slit lamp, when that system becomes available. The theory involved in focusing the beam to a very small spot on the desired target and the determination of depth of incision in corneal tissue is contained in Chapter III. In Chapter IV the experimental apparatus and procedure used in this study are discussed in detail; Chapter V contains the various results; and Chapter VI includes the conclusions and recommendations.

II Background

The application of the laser as a surgical instrument came as a result of studies in laser safety and the development of the laser for use in industry and the military (Ref 3:173). Because of its ability to produce coherent, monochromatic light of high power density, it is today an important surgical tool. The laser has achieved favorable results in general surgery (Ref 4), dermatology (Ref 3:184), burn surgery (Ref 5), otolaryngology (Ref 6), laryngology (Ref 7), gynecology (Ref 8:22), and ophthalmology. Three lasers are generally employed in ocular surgery: the ruby, the argon and the carbon dioxide laser. The first two lasers are used as photocoagulators while the third has been used successfully in the treatment of glaucoma. A basic knowledge of the eye is a necessary prerequisite to understanding how these lasers affect different ocular elements.

The Human Eye

Figure 1 is a cross-section of the human eyeball. The outer transparent layer of the eye, centered on the front of the eye, is called the cornea. It provides the major refraction of the eye due to its curvature. The cornea is surrounded by the sclera, a tough, white, outer layer.

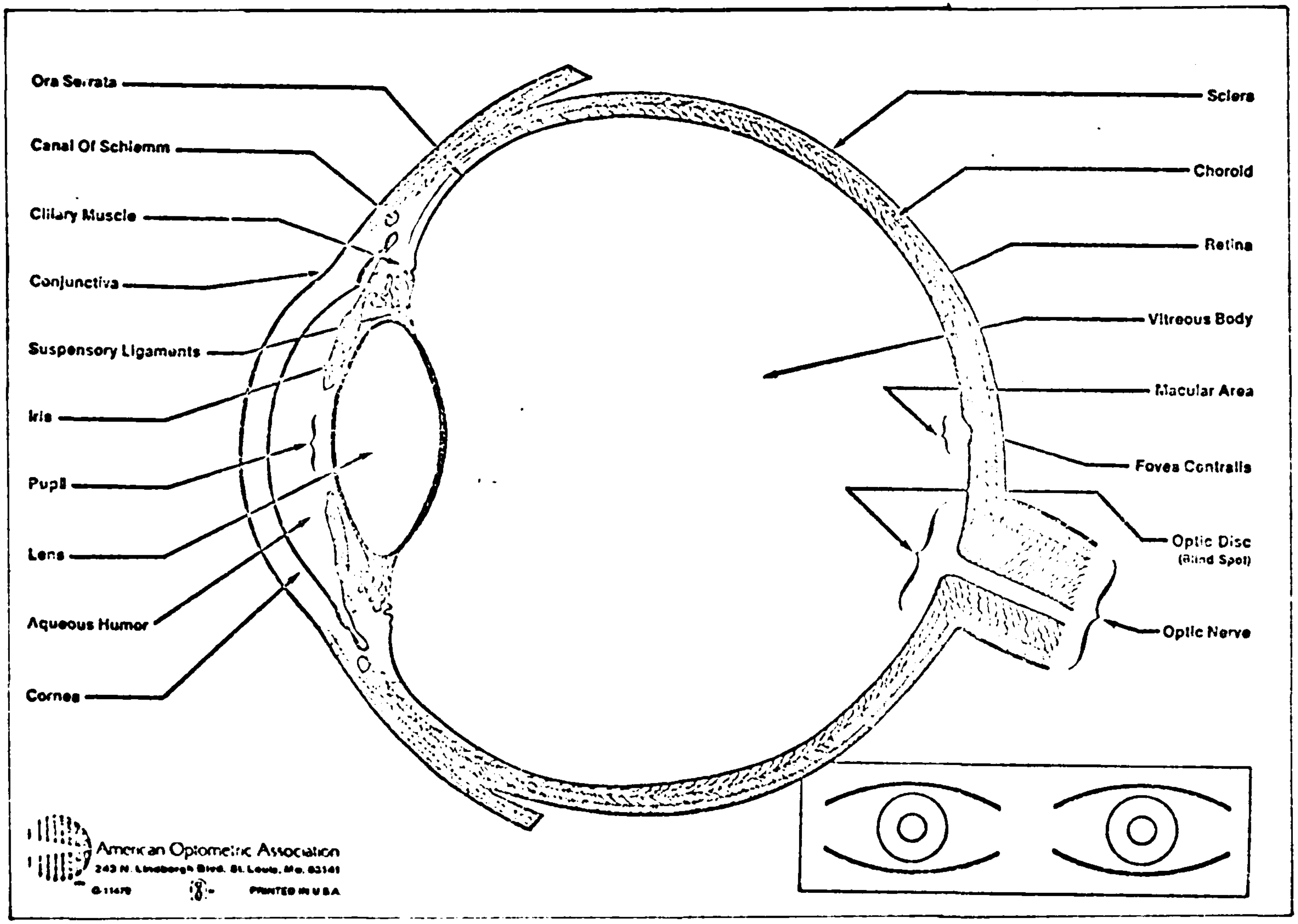

Figure 1. Schematic Section of the Human Eye

Visible light passes through the cornea and the aqueous humor. The aqueous humor, a watery fluid, fills the front chamber of the eye and furnishes some of the nutrition for the surrounding parts. The round hole in the center of the iris is the pupil. It ordinarily appears black since there is no light emanating from the chamber behind it. Directly behind the pupil is the lens. It is a transparent structure which can change its shape and hence focus incoming light. Once light passes through the lens into the vitreous humor, it is brought to a focus on the retina. The retina is the inner lining of the rear chamber of the eye. It contains the layers of nerve cells which give the eye its sensitivity to light. Between the retina and sclera is a layer called the choroid. It primarily contains blood vessels which provide nourishment to the retina. The optic nerve is the bundle of fibers which carry vision related impulses from the retina to the brain (Ref 9:607-612). Specifically, the cornea contains five distinct layers as shown in Figure 2 (Ref 10:13). The first is the epithelium, a layer of cells 50 μm thick. These cells have a turnover rate of approximately 10 days and a healing rate of only a few hours. At the basement membrane of the epithelium is Bowman's layer. It is 10-14 μm thick. Below this layer is the stroma which makes up about 90% of the corneal thickness. It consists of collagen fibrils arranged in bands which run

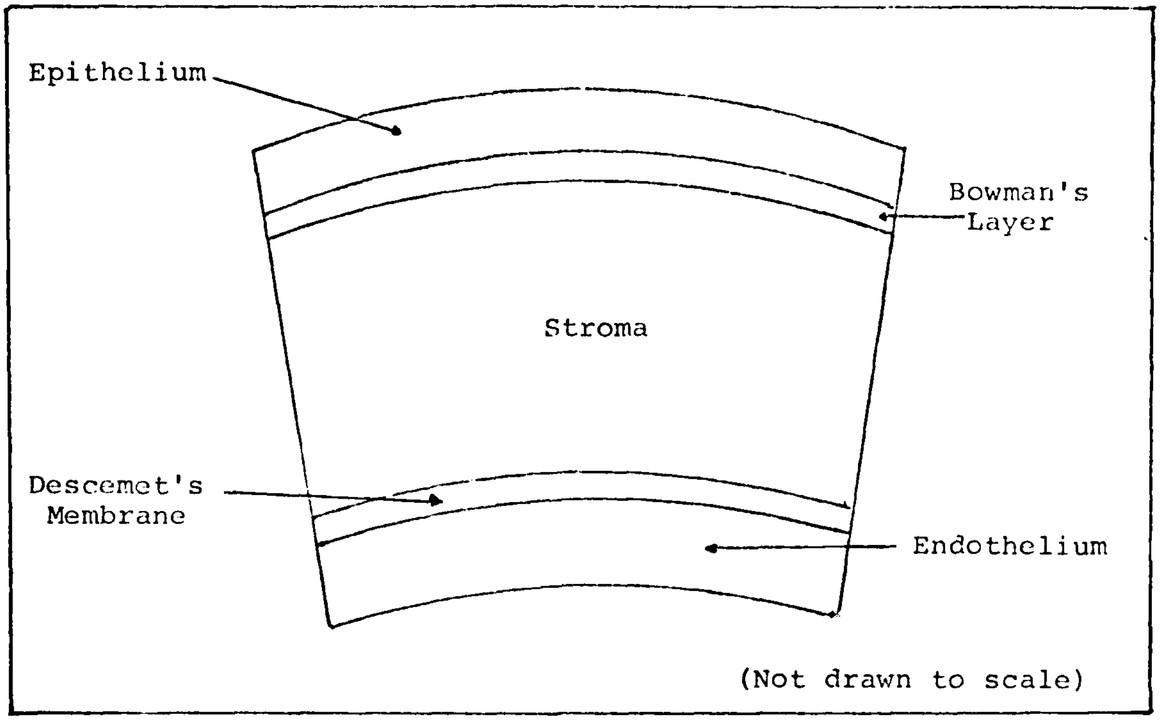

Figure 2. Corneal Cross-Section

parallel to the surface. Below the stroma is Descemet's membrane, a thin, elastic layer of cells, easily detached from the stroma (Ref 11:19). The underlayer of the cornea is the endothelium, one cell thick. This layer of the cornea is extremely heat sensitive so that great care must be taken not to alter its temperature very much. The entire thickness of the cornea is about 0.5 mm at the center.

Ruby Laser Photocoagulator

The retina and blood vessels in the retina are very fragile. In most parts of the body, a break in a blood vessel is only a minor injury and the body can repair the damage by itself. When a blood vessel ruptures in the eye and drops of blood enter the vitreous humor, the loss in visual acuity may be severe. The blood in the vitreous can create blindness by blocking the incoming light. Also, the blood can cause the retina to swell and tear loose from the choroid.

With the invention of the ruby laser, the ophthalmologist was provided an effective means of photocoagulation. It proved to be more effective than the old xenon arc lamps which were used prior to 1960. However, there were several engineering problems associated with the ruby laser. The laser used a capacitor bank to charge the flashlamp and the ruby rod needed time between pulses to cool. Both of these characteristics limited the number of pulses per minute. Also, the high peak powers produced in the 50 nanosecond Q-switched pulses caused large acoustic waves in tissue (Ref 12:1520).

Argon Laser Photocoagulator

L'Esperance proposed the use of the argon laser as a photocoagulator since blood is highly absorptive at the emission wavelengths of the argon laser, 488 nm and 514.1 nm. This laser is capable of heating and coagulating blood in the vitreous humor. Its radiation also leads to reabsorption of the fluid separating the retina from the choroidal tissue and returning the retina to its original position (Ref 12:1521).

A fascinating use of the photocoagulator involved a female patient with a worm in her eye (Ref 3:181). The worm, in its larval form, used a frog as a host. The woman had evidently prepared frog legs for cooking without wearing gloves to protect her hands. As the woman was touching the frog leg, the worm came off the frog and onto her hand. Later, she touched her eye with the finger the worm was on and the worm became lodged in her eye. It was successfully exterminated with the argon laser.

The laser manufacturer, Coherent Radiation, has a commerically available argon photocoagulator. It consists of a Zeiss photo-slit lamp integrated with an argon laser (Ref 13). A console houses the laser tube, power supply, and shutter assembly. A fiber optic transmits the radiation from the console to the slit lamp. The spot size is continuously adjustable from 50 to 2000 μm. The laser power can be varied from 0 to 2.0 W and the exposure time can be set from 0.02 to 5 seconds or the laser can be operated in a continuous (CW) mode.

CO_2 Laser

While visible light passes through the cornea, infrared radiation is almost completely absorbed. The CO_2 laser is therefore ideal for vaporizing tissue and making incisions on the cornea and other ocular tissue. Only a few attempts have been made to use the CO_2 laser in ophthalmology. One method that was being evaluated involved changing the curvature of the cornea through irradiation with 10.6 μm laser light (Ref 14;15;16;17). All of the studies were conducted on rabbits. The authors reported that, following exposure to the radiation, the corneal curvature decreased significantly. However, after a few weeks, the cornea resumed its original shape. The spot sizes used were no smaller than 100 μm with power levels between 1 and 12 W. Peyman suggested that with repeated laser pulses over a period of time, the procedure could prove more effective.

Another use of the CO_2 laser in ophthalmology involves the "laser knife," a substitution for the scalpel. There are two important advantages of the laser knife. First, the surgeon is actually in better control of the laser than a scalpel since there is no frictional drag (Ref 16:78). Also, the CO_2 laser emits invisible radiation and, unlike a scalpel, does not obstruct the ophthalmologist's field of view.

In 1971, Beckman and his colleagues performed corneal and scleral dissections on rabbits (Ref 18). They used a rapid (20 - 150 pulses per second) "superpulsed" CO_2 laser capable of a power of

25 kW and an average output power of 150 W. With the rapid super-pulsed mode set at 0.4 J per pulse, only minor tissue destruction was observed around the vaporized area. Using a diverging prismatic lens, the authors were able to use the laser as an optical trephine and remove a circular area of the cornea. Also, they created a hole, 1 mm in diameter, through the sclera, opening into the anterior chamber. This procedure is called a limbectomy. In both operations, the laser penetrated into the anterior chamber and caused the aqueous humor to vaporize.

More recently, Beckman and Fuller employed a CO_2 laser for scleral dissection on human eye-bank eyes and a filtering procedure for glaucoma on human eyes in situ (Ref 1:19). In a normal eye the aqueous humor flows out of the posterior chamber of the eye through the trabecular meshwork. Glaucoma results when the trabecular meshwork becomes clogged. In this study, the authors used a CO_2 laser in both the rapid superpulsed and CW modes, and a series of lenses that varied the spot size from 200 μm to 1.25 mm.

One objective of the study was to investigate which laser mode of operation, the rapid super-pulsed or the CW mode, resulted in the greater spreading of heat from the point of laser impact into the surrounding scleral tissue. The mode which created the least temperature change around the point of laser impact would be used in the filtering operations. A copper constantan thermocouple was located in the sclera at varying distances from the point of laser contact. On nine eye-bank eyes, a series of 160 lesions were made, half with the laser in the rapid super-pulsed mode and half in the CW mode. The results indicated that the rapid super-pulsed mode of operation is optimum because there is less time over which the laser beam is in contact with the tissue and therefore the rapid super-pulsed mode thermally affects adjacent tissue less than the CW mode.

Thus, the rapid super-pulsed mode was selected to perform the filtering operation. On five patients with glaucoma, a large flap of conjunctiva was dissected. Then, with the rapid super-pulsed repetition rate of 120 pulses per second, average power of 5 W, pulse width of 150 milliseconds, and spot size of 600 μm, a hole was made into the anterior chamber. The eyes were examined over a six month period and all were found to have characteristics which were identical to the conventional filtering procedure.

The effects of the CO_2 laser on the lens and vitreoretinal tissue were also examined (Ref 20). The CW mode laser was set for a 100 μm spot diameter at a variety of powers up to 9.0 W. A series of graphs of depth-of-incision versus laser power for the sclera and lens indicated a linear relationship. The results indicated that the CO_2 laser may be beneficial in intra-vitreal surgery.

Several important observations concerning the above experiments with the CO_2 laser need to be emphasized. First, the laser beam was never focused to a spot diameter of less than 100 μm. Also, in some cases, the beam was permitted to penetrate into the acqueous humor, partially vaporizing it. In corneal surgery, both situations are unacceptable on a living patient. The laser must be focused to a smaller spot size and, in addition, the depth of the incision must be precisely controlled so that the endothelium is not damaged and the aqueous humor not heated.

Applications in Corneal Surgery of CO_2 Laser Scalpel

Once a reliable and safe CO_2 laser optical system can be incorporated with a slit lamp, in a manner similiar to the argon photo-coagulator referred to earlier, the ophthalmologist will have an instrument that will supplement and even replace his scalpel in some surgical procedures. These include, for example, radial keratotomy, corneal transplants, relaxing incisions following corneal transplants, and rapid and precise cutting of surface sutures.

The newest method of radial keratotomy is called the Fyodorov method (Ref 21:141-172). This technique is just in the experimental stage and already (mainly due to publicity) thousands of myopic people are undergoing radial keratotomies to improve their visual acuity (Ref 22; 23; 24).

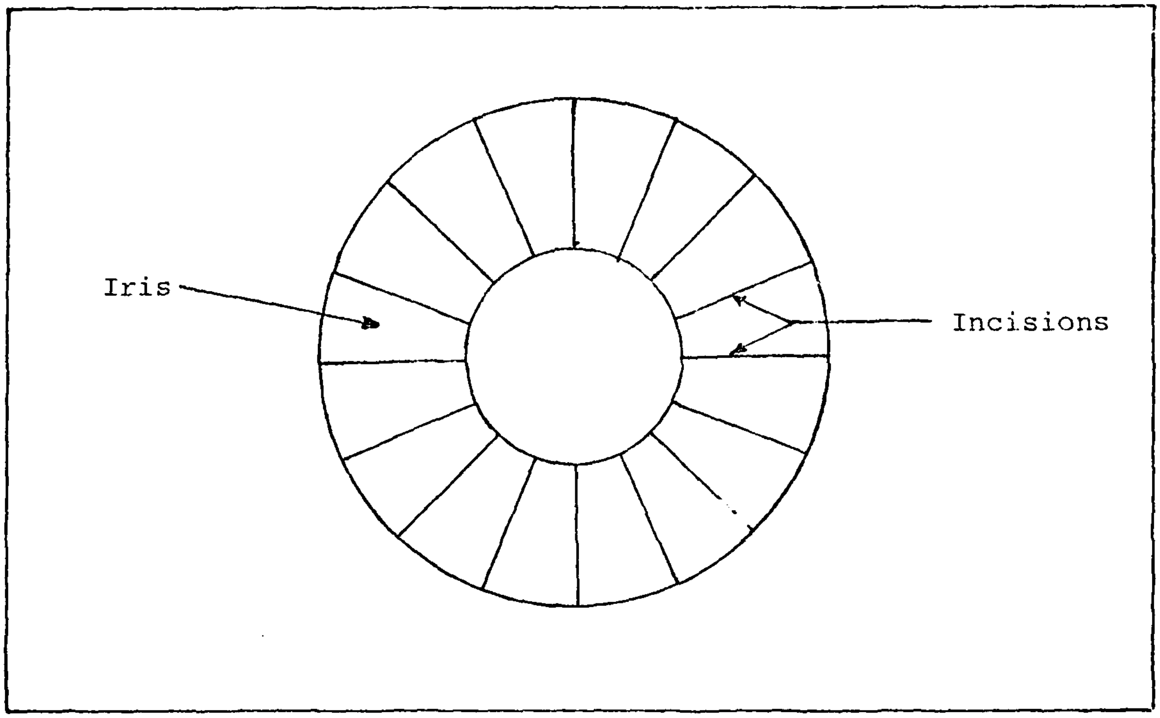

Figure 3. Fyodorov Method

Myopia or nearsightedness occurs when the distance between the cornea and the retina is too long and therefore distant objects appear blurred. The Fyodorov technique consists of making 16 radial incisions as shown in Figure 3. The depth of each incision is determined by the degree of refraction and several other factors. Following the incisions, the central section of the cornea flattens out, bringing it closer to the retina. Dr. Fyodorov has performed the operation on 2600 patients in the Soviet Union. In this country, radial keratotomy is just beginning to be tested (Ref 25:173-174; 26:175-182).

The physics behind the success of the operation is also just beginning to be understood. The major variables, based mainly on experimental results, are intraocular pressure; the elastic constants of the collagen fibrils; the corneal radius of curvature, thickness, and diameter; and depth and length of incisions (Ref 27:195-220). Schachar and his associates developed a mathematically complicated basic strength of material analysis applied to a dome. Their computer results are consistent with clinical findings and allow them to predict the depth of the incision and the size of the optical zone necessary for a given change in curvature.

The correction of myopia by means of the Fyodorov method requires special scalpels in the hands of skilled ophthalmologists. As mentioned above, the success of the operation is dependent upon the precise length and depth of the incision. A guarded razor-blade knife is generally used. Some ophthalmologists have gone to a micrometer type of knife. Once the incisions are complete, a special depth gauge is inserted into the incision to make certain it is uniform and of the desired depth. If they are not deep enough, the procedure must be repeated. The ophthalmologist must be careful that he does not push the blade too hard, otherwise the knife will enter the aqueous humor. Dr. Fyodorov has reported this happening in several cases.

With the proposed CO_2 laser optical system, the Fyodorov method may be less difficult to perform. The problem of applying the exact pressure on the scalpel is eliminated. A laser "knife" capable of penetrating the tissue as little as 10 μm per irradiation may result in incisions which are more exact in depth than those performed with a scalpel. By selecting the correct output power and cutting speed, the laser can make the incisions without the danger of entering the aqueous humor. Also, instruments such as the scalpel are not present to block the ophthalmologist's field of view. In addition, he will be in better control of the laser beam than he would a scalpel since there is no frictional drag associated with movement of the laser beam.

If the operation is ultimately successful, millions of Americans with myopia may no longer need to wear glasses. Individuals with myopia will be able to drive cars, participate in sports, and do other daily tasks without their glasses. Young people who wish to become pilots need not be rejected as candidates because they are nearsighted. Their vision could be corrected by a 15 minute operation. As Fyodorov said: "We feel that in the future, people will build monuments with their obsolete glasses."

Another type of corneal surgery where the laser may replace the scalpel is corneal transplantation or keratoplasty. The procedure is shown in Figure 4. In (a), a

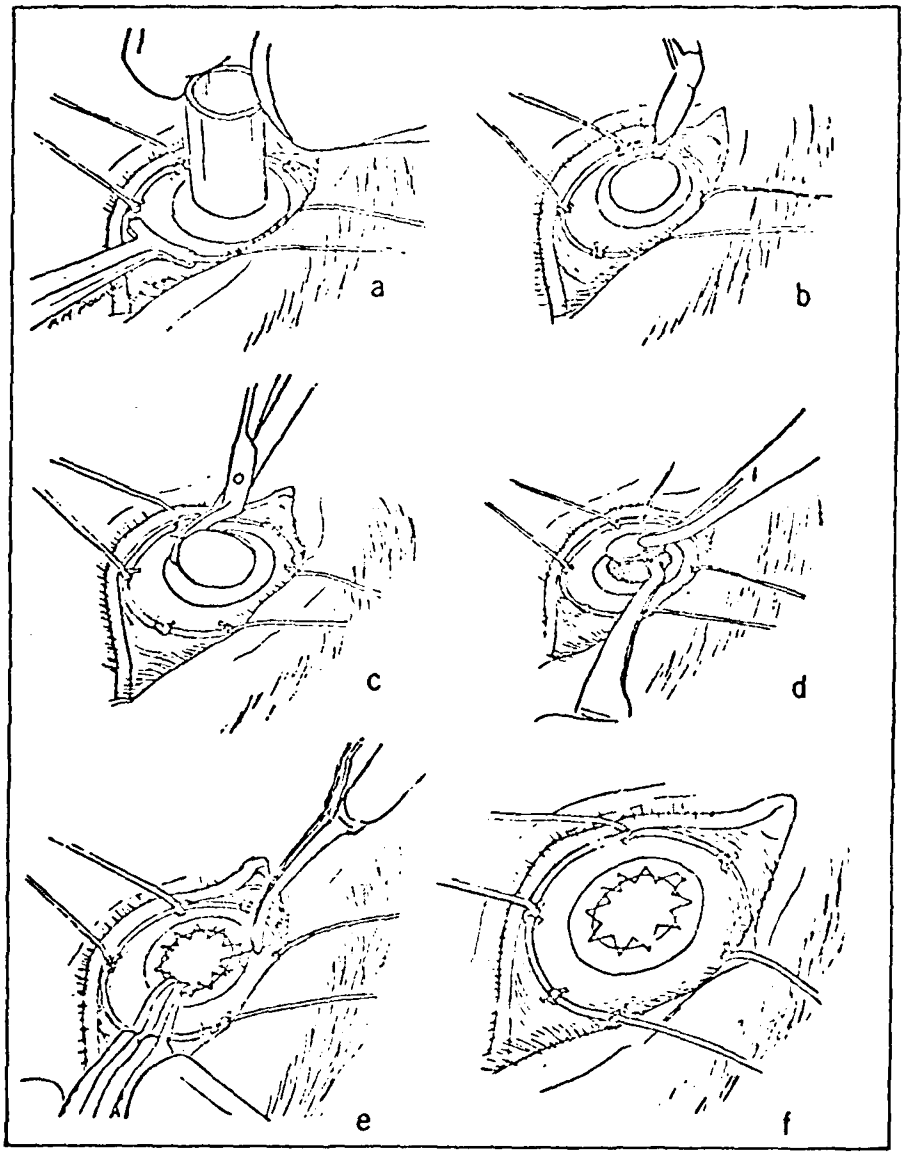

Figure 4. Corneal Transplantation

trephine is used to make a superficial corneal cut. A razor-blade knife makes the incision deeper (b). With corneal scissors, the corneal button is excised (c). The new button is held in place with forceps while the first suture is implanted (d). Four cardinal interrupted sutures secure the graft until a running suture is placed (e). Finally, the completed operation is shown in (f).

With a computer driven CO_2 laser, the light "scalpel" may be able to take the place of the trephine and knife in this operation. This idea was suggested as early as 1975 (Ref 28:231), but as far as known, has not been attempted. The beam could be guided in a circle of a preset radius and automatically make the incision. It may also cut the new corneal button from the donor eye. The laser could make the incisions more accurately than the trephine and razor-blade knife.

Once the graft has healed, the sutures must be removed. In some cases, the suture may be ruptured with the laser beam instead of a scalpel. If the beam is focused to a spot diameter equal to the thickness of the suture, the laser beam will cut (vaporize) the suture with less damage to the cornea than the routine method.

Sometimes the new corneal button will heal nonuniformly. The ophthalmologist must then make so-called "relaxing incisions" where the cornea is asymmetrically stretched.

These incisions will bring the cornea back to a uniform curvature. As with the Fyodorov method of radial keratotomy the depth of the incision is critical. Therefore, the laser may be ideally suited to make these incisions.

III Theory

The objective of this thesis, to design a CO_2 laser system to make razor-like incisions on the cornea, requires an understanding of how to focus a Gaussian laser beam to an extremely small spot on the cornea and vaporize the tissue at the point of contact. The corneal tissue must absorb the CO_2 laser radiation, convert the energy into heat, and, in turn, vaporize.

Focusing a Gaussian Laser Beam

In order to obtain a fine incision, the beam must be focused to a spot size of approximately 25 μm or smaller. The following equation is used to determine the focal length of a lens, given the value of the spot size to which the beam is to be focused (Figure 5) (Ref 29:31).

$$\frac{1}{W_{O2}^{2}} = \frac{1}{W_{O1}^{2}}\left(1 - \frac{Z_1}{f}\right)^2 + \frac{1}{f^2}\left(\frac{\pi W_{O1}}{\lambda}\right)^2 \qquad (1)$$

where

W_{O1} = beam waist radius of laser beam incident on focusing lens

W_{O2} = beam waist radius of laser beam after focusing

Z_1 = the distance from the beam waist of the incident beam to the focusing lens

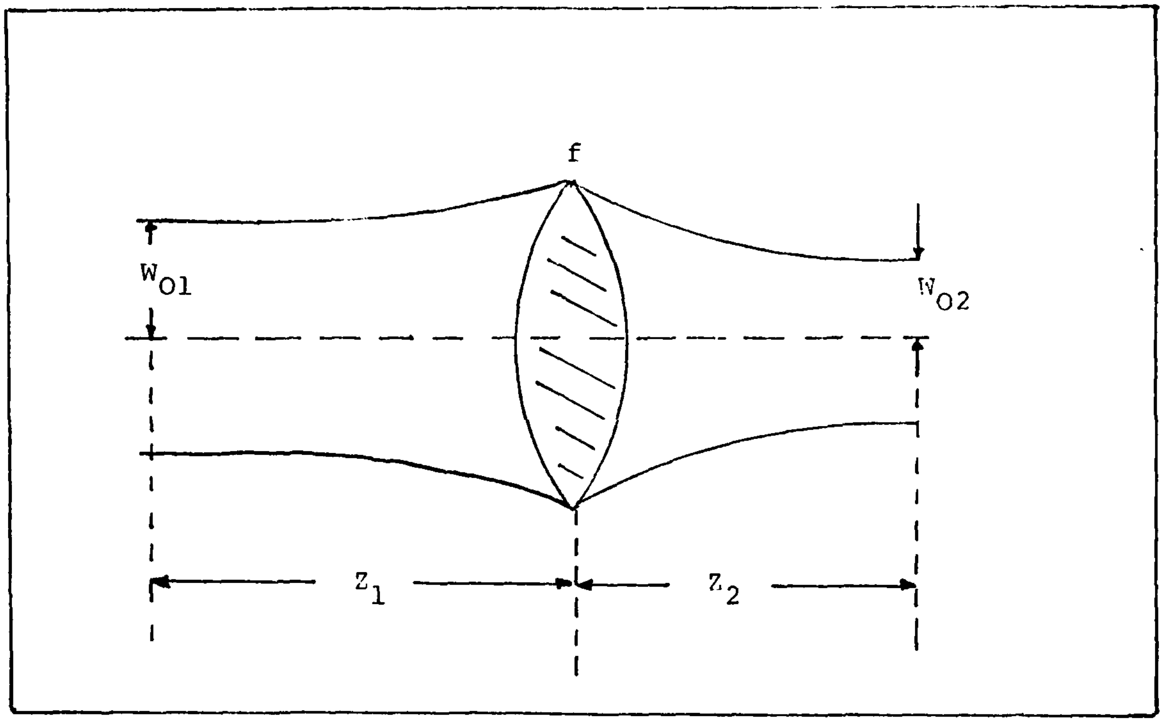

Figure 5. Focusing a Gaussian Laser Beam

f = the focal length of the lens
and λ = the wavelength of the laser.

Equation (1) can be written as:

$$f = \frac{\dfrac{-Z_1}{W_{01}^{2}} \pm \left\{ \left(\dfrac{Z_1}{W_{01}^{2}} \right)^2 + \left(\dfrac{1}{W_{02}^{2}} - \dfrac{1}{W_{01}^{2}} \right) \left[\dfrac{Z_1^{2}}{W_{01}^{2}} + \left(\dfrac{\pi W_{01}}{\lambda} \right)^2 \right] \right\}^{\frac{1}{2}}}{\dfrac{1}{W_{02}^{2}} - \dfrac{1}{W_{01}^{2}}} \tag{2}$$

For the laser used in this experiment, $W_{01} = 3.15$ mm and $\lambda = 10.6$ μm. If $W_{02} = 25 \times 10^{-3}$ mm and $Z_1 = 1.0$ m, then $f = 24.60$ mm.

Unlike the predictions of geometrical optics, the laws which govern the propagation of Gaussian laser beams indicate that collimated beams will not necessarily be brought to a focus in the focal plane of the lens. In Gaussian optics, W_{02} is focused at (Ref 29:31):

$$Z_2 = f + \frac{\left(Z_1 - f\right) f^2}{\left(Z_1 - f\right)^2 + \left(\frac{\pi W_{01}^2}{\lambda}\right)^2} \qquad (3)$$

With the values mentioned above, $Z_2 = 24.65$ mm, which, for all practical purposes, is at the focal plane.

The laser beam may be focused to an even smaller spot size, without changing the focusing lens, by introducing a beam expander in front of the lens. A Galilean-type beam expander consists of an appropriate negative/positive lens combination as shown in Figure 6. Suppose f_1 is the focal length of the left lens (negative) and f_2 is the focal length of the right lens (positive). A nearly collimated beam (beam diameter = D_i) which enters the beam expander and just fills the negative lens will, upon striking the positive lens at the output end of the beam expander, just fill the positive lens with an increased beam cross-section ratio of f_2/f_1. As a consequence, the laser beam leaving the beam expander is rendered even more parallel by a factor of f_2/f_1.

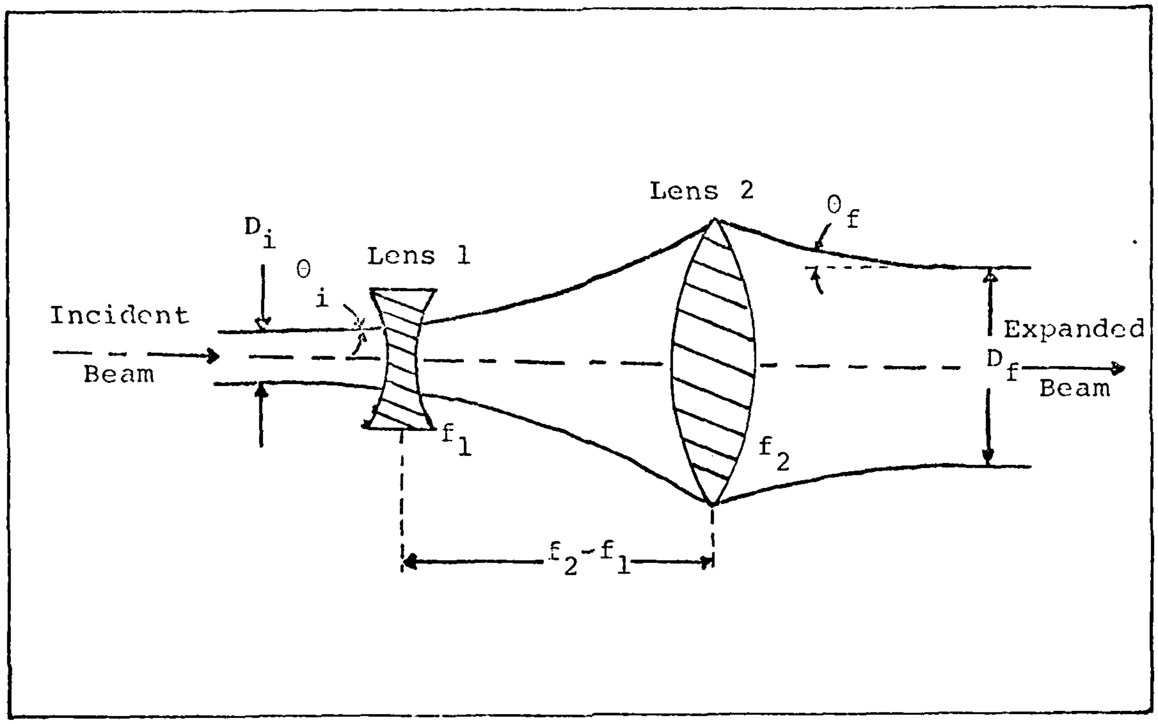

Figure 6. Galilean-Type Beam Expander (Ref 29:31)

Mathematically

$$\theta_f = \left(\frac{f_1}{f_2}\right)\theta_i \tag{4}$$

where

θ_i = the half-angle beam divergence of the incident beam and θ_f = the half-angle beam divergence of the expanded beam. Therefore, with the beam expander included and the aperture of the focusing lens made at least as large as the diameter of the expanded beam, the predicted spot size is:

$$\frac{1}{W_{02}{}^2} = \left(\frac{f_2}{f_1}\right)^2 \left[\frac{1}{W_{01}{}^2}\left(1 - \frac{Z_1}{f}\right)^2 + \frac{1}{f^2}\left(\frac{\pi W_{01}}{\lambda}\right)^2\right]$$

or

$$W_{O2} \simeq f\left(\frac{f_1}{f_2}\right)\Theta_i \qquad (5)$$

Equation (5) assumes W_{O1} is much greater than W_{O2} and Θ_i is very small. In this problem both assumptions are valid. In effect, then, the introduction of a beam expander of ratio f_2/f_1 enables a focusing lens of focal length f to image the beam to a spot size f_2/f_1 times smaller than the focused spot size without the beam expander.

One problem arises with the use of very small focused spot sizes. The Rayleigh range, the distance from the focal plane to a position where the beam area has doubled its original size, is given by (Ref 29:30):

$$Z_R = \frac{\pi W_{O2}^{\ 2}}{\lambda} \qquad (6)$$

If, for example, the focused spot size is decreased by a factor of 5 (beam expander ratio $f_2/f_1 = 5$), then Z_R is decreased by a factor of 25. The beam radius at a distance Z from the focal plane is given by (Ref 29:30):

$$W(Z) = W_{O2}\left[1 + \left(\frac{\lambda Z}{\pi W_{O2}^{\ 2}}\right)^2\right]^{\frac{1}{2}} = W_{O2}\left[1 + \left(\frac{Z}{Z_R}\right)^2\right]^{\frac{1}{2}} \qquad (7)$$

With the aid of equation 7, Figure 7 shows how the spot diameter grows as a function of distance from the focal

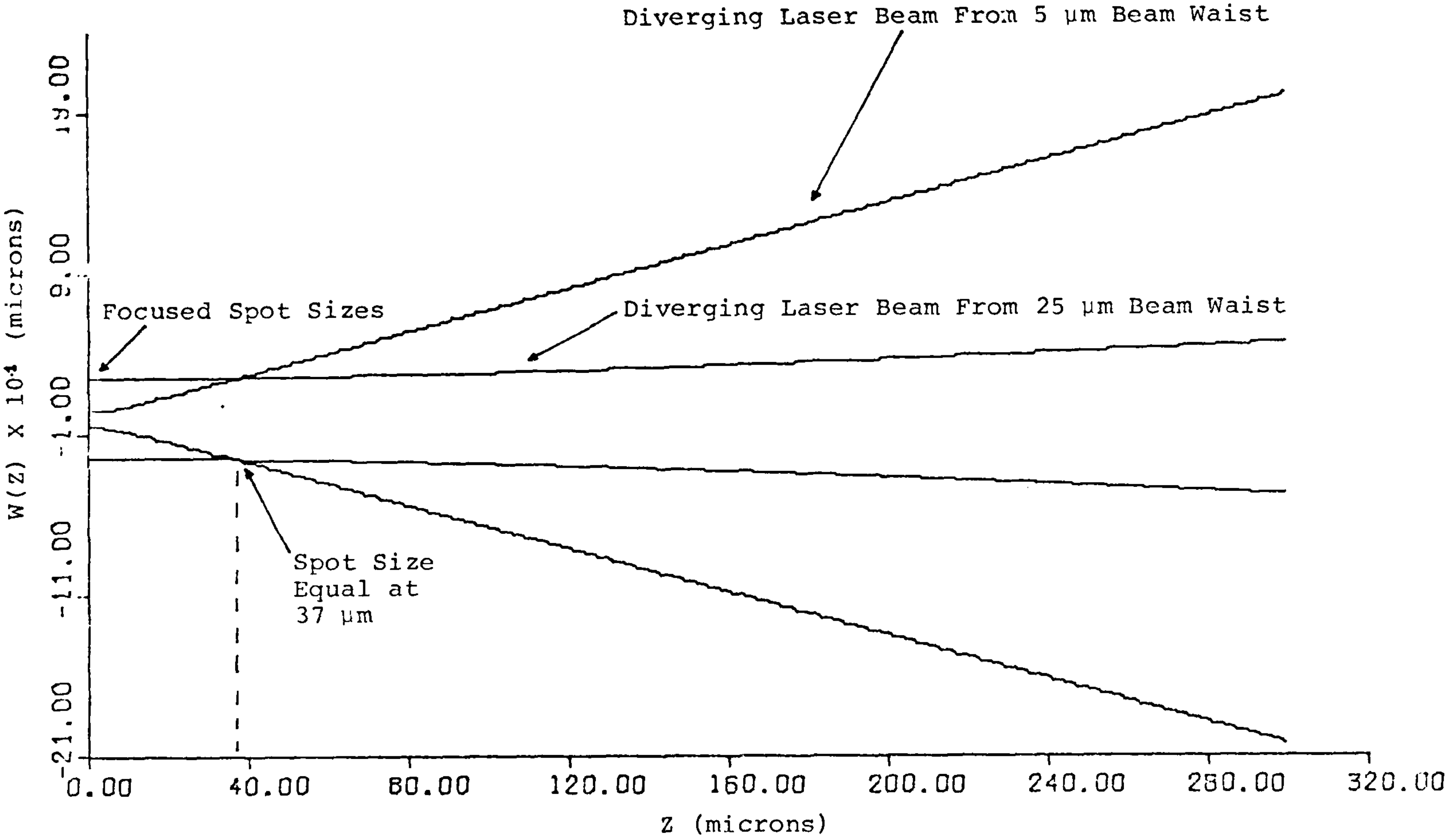

Figure 7. Spot Diameter versus Distance from Focal Plane

plane out to 300 μm, for focused spots of 25 μm diameter and 5 μm diameter. At 37.0 μm from the focal plane, the diverging spot sizes are equal and at 80 μm, the beam diverging from the 5 μm spot size is already twice the size of the beam diverging from the 25 μm spot size. Consequently, the intensity (power/beam area) of the diverging beam which was initially expanded before being focused will decrease very rapidly compared to the intensity of the initially non-expanded beam. In Figure 8, the intensity (power = 1.0W), in W/cm^2, is plotted versus distance from the focal plane for both the initially expanded and unexpanded beams.

Depth of Corneal Incision

Predicting the reaction of a laser impact on the cornea is an extremely difficult problem. Living tissue is complex and heterogeneous. According to Goldman (Ref 30:59), there are three possible reactions of a laser impact on tissue: a thermal component, pressure recoil and elastic shock waves, and with high energy densities some electromagnetic field changes may occur.

In the following analysis, a first order attempt to calculate the depth of a corneal incision will be examined. It is based solely on the thermal reaction and does not include the other two components mentioned above. The theory is based on several assumptions. First, the thermal

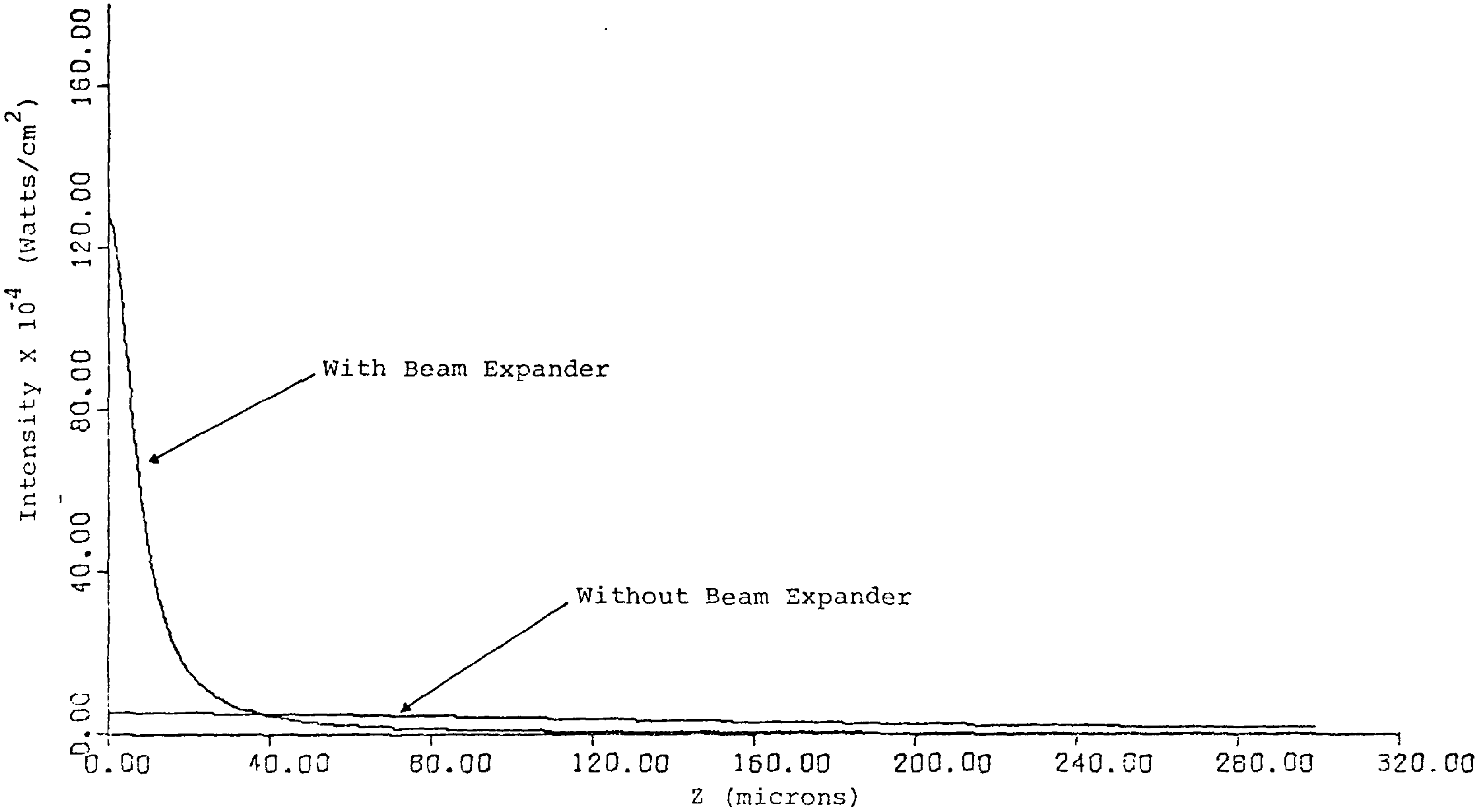

Figure 8. Intensity versus Distance from Focal Plane

properties of the cornea (as well as all living tissue) are well represented by water (Ref 31:8;32:323). Since the cornea consists of approximately 20% collagen and 80% water by weight (Ref 31:8), this assumption is reasonable for a first order calculation. The thermal properties used in the analysis are listed in Table I. The second assumption is that the energy loss due to thermal diffusion and radiation is negligible. In addition, it is assumed that the gas created when the tissue vaporizes is itself transparent at the wavelength of the laser. Finally it is assumed that the laser energy is totally absorbed by the tissue and the laser beam intensity does not change with increasing depth or penetration. Although these assumptions may seem somewhat severe, they represent a reasonable starting point for a first order approximation.

With these assumptions in mind, the energy of the laser (in calories) incident on and totally absorbed by the cornea is:

$$E = pV\left[C(T_V - T) + L\right] \tag{8}$$

where V is the volume of the cornea being vaporized and the other quantities are listed in Table 1. The volume can be rewritten as:

$$V = Ad$$

TABLE I

Thermal Properties of the Cornea (Ref 31:50)

Heat capacity (C)	: 1.0 cal/g-^{o}C
Normal corneal temperature (T)	: 35 ^{o}C
Boiling temperature (T_v)	: 100 ^{o}C
Density (p)	: 1.0 g/cm^3
Latent heat of transformation (liquid to gas) (L)	: 539 cal/g

where A is the laser beam area (cm^2) and d is the depth of the incision (cm). Using the values given in Table 1, equation (8) may be written as:

$$E = 2525 \; (\; Ad \;) \tag{9}$$

where E is now measured in joules. The depth of incision d, as a function of laser output power and pulse duration can then be determined from

$$d = \frac{P \;\; \Delta t}{2525 \; A} \tag{10}$$

where P is in watts and Δt is in seconds.

IV Experimental Apparatus and Procedure

The CO_2 laser optical system basically consists of a laser, focusing optics, and a motorized mount. A detailed description of the components of the system, the test material, and the procedure used in the study is given in this chapter.

Experimental Arrangement

Figure 9 is a schematic view of the optical system. It consists essentially of a CO_2 laser, an external mechanical chopper, an optical shutter with a foot switch, a laser beam expander, a focusing lens, and a target area attached to a motorized mount. The Coherent Radiation Model 42L CO_2 laser (Figure 10) operates in either the CW mode or in the Q-switched mode. In the far field the laser has a beam divergence of 1.1 milliradians. When it is operating in the CW mode, the output power may be set anywhere from 0 to 50 W. The internal mechanical Q-switch (Coherent Radiation Model 152L) is located in the intra-cavity space between the plasma tube and the output mirror. The chopper wheel in the Q-switch consists of 18 equally spaced slots and is driven by a motor at 400 cycles per second. This produces a pulsing frequency of 7.2 kHz and a pulse length of 500 nanoseconds (Figure 11). The maximum average power is

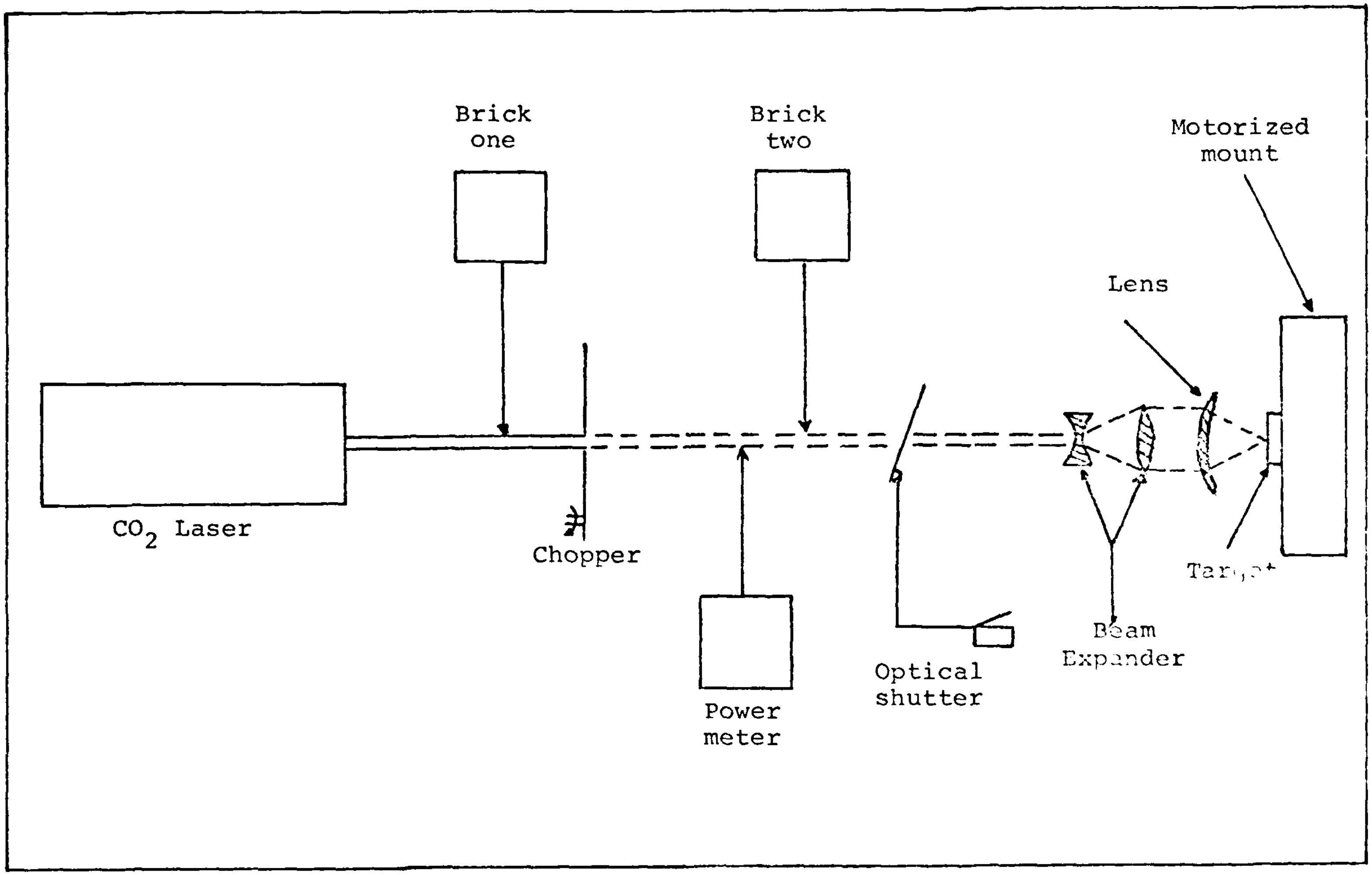

Figure 9. Schematic of Experimental Setup

Figure 10. CO_2 Laser

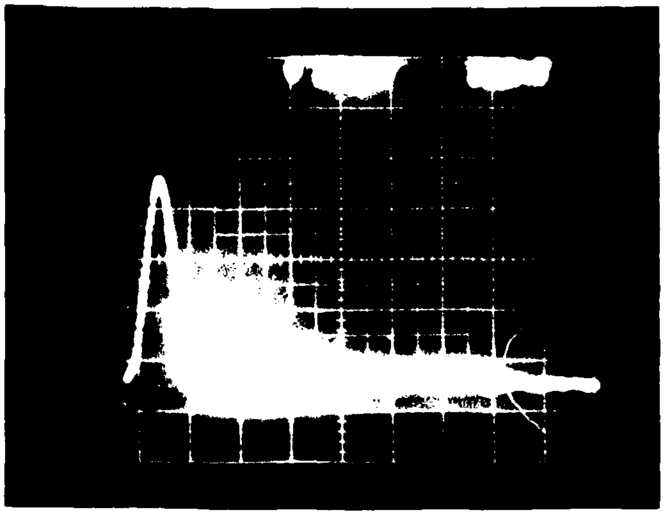

Figure 11. Q-Switched Laser Pulse

1.8 W, which results in a peak power of 500 W. It has a 0.36% dutycycle.

Two different external mechanical choppers were tested while operating the laser CW. For each, the chopper wheels were driven by a motor at 30 cycles/sec. One chopper consisted of three equally spaced slots and consequently chopped the laser beam at 90 pulses/sec. It had a 10% dutycycle and cut down the average incident power by 90%. The other chopper had 15 equally spaced slots, produced a pulsing frequency of 450 pulses/sec, and had a 50% dutycycle, thereby leading to a 50% reduction in average power. The size of the slots in both choppers were equal and resulted in a pulse duration of 1/900 second.

In order to obtain a power level below 4.0 W at the entrance plane of the chopper, a GTE Sylvania CO_2 Laser Attenuator (Model 485) was used. With the attenuator, the laser power could be varied from 2% to 95% of the incident power. The degree of attenuation was varied by manual rotation of a calibrated dial on the output end of the attenuator. The dial was marked in 2-degree increments from 0 to 360°. The internal walls of the attenuator housing absorbed the reflected power from the germanium windows. The attenuator was only used when the average power incident on the focusing lens was required to be below 0.4 W.

The optical shutter is a 2.0 cm wide aperture Graphex shutter. The exposure setting are adjustable from 1/400 to 1/2 seconds. The shutter is connected to a 6 volt battery and a foot switch.

The next component of the system is a beam expander. This expander is manufactured by II - VI Inc. and consists of two zinc-selenide lenses. It is designed so that by changing the input diverging lens and adjusting the inner tube to the proper position, the beam expansion ratio is changed to any desired ratio from 2:1 to 5:1. The input lens used in this experiment provided a beam expansion ratio of 5:1.

The meniscus focusing lens is made of germanium with anti-reflection coatings. It has a 3.3 cm focal length. From equation 1 such a lens theoretically focuses the beam to a 33.6 μm spot size without the beam expander and 6.7 μm with the beam expander ratio set at 5.

The target to be irradiated is affixed to a Motomatic motorized x-y mount (Figure 12). The speed of the mount, in either direction, is adjustable from 1 cm/min to 270 cm/min. When irradiating a test cornea, a stream of inert gas (argon, in this case) is directed onto the surface of the cornea to reduce charring as the laser beam penetrates and vaporizes the tissue.

Figure 12. Motorized Mount

The target is viewed using a C. Baker stereoscopic microscope. This microscope gives an enlargement ten times the actual size of the irradiated object.

Test Material

In order to obtain preliminary measurements on the spot size of the focused beam, thermal copying paper was used. This paper is quite heat sensitive and works well as a rapid "calibration" material. The thermal paper used in this experiment was over 10 years old. It appeared pink on one side and white on the other. The pink side was more sensitive to heat and was therefore used as the target face.

Clear plastic sheets from wraparound cover of government issue document protectors were also used. The width and quality of "incisions" is then evaluated at varying target mount speeds, power settings, and sweep numbers. The two calibration materials used here give a reasonable indication of what to expect in a corneal incision.

To illustrate precise beam control, an experiment was performed on 9-0 Ethicon surgical suture. The suture was black and approximately 50 μm in diameter. The object of this particular demonstration was to determine the minimum power and exposure setting necessary to just rupture the suture with minimum laser beam penetration behind the suture.

For tests of laser beam control approaching a more realistic target, bovine and hog corneas (both obtained from a local abattoir), and human corneas (obtained from Ohio State University Eye Clinic) were used. The techniques of storing and preserving the corneas are explained in the Appendix. The bovine eye is by far the largest of the three. It has a cornea approximately 2 cm in diameter, while the hog cornea is 1 cm and the human cornea is 0.6 cm in diameter.

The cornea is removed with a trephine and corneal scissors, before mounting, or the entire eye may be mounted on the translator. If only the cornea is mounted, it is attached to an index card with transparent tape. The tape must not come in contact with the portion of the cornea to be irradiated, since the epithelium is very sensitive and the tape may damage this delicate layer. If the cornea is removed from the eye before irradiation it is advisable to leave a ring of the sclera surrounding the cornea. Then the sclera ring can be taped to the card without damaging the epithelium.

In most cases, irradiating the cornea while it is still part of the globe of the eye is easier. An eye holder is used to mount the globe of the eye onto the translator (Figure 13). The globe is placed between four prongs and secured with a rubber band. The rubber band closes the prongs around the eye and holds it in place. A strip of thermal paper is taped to the side section of the holder (just to the left of the eye in Figure 13). The laser beam can then be focused on the paper insuring that, if the paper is coplanar with the cornea, the laser is also focused on the cornea. Also, the eye can be kept moist by placing a few drops of saline solution at the top of the eye and letting the solution flow down over the front surface of the cornea.

Figure 13. Eye Holder

Experimental Procedure

This procedure refers to the layout of equipment described previously in Figure 9.

1. Brick one is placed in front of the output mirror of the CO_2 laser to obstruct the beam. It acts as an on-off switch so that the components of the system can be rearranged without turning the laser off.
2. The laser is turned on and allowed to warm up for five minutes. The lowest output power achievable 4 W while operating in the CW mode, is obtained

for laser tube settings of 4 mA current and 25 mm of Hg pressure.

3. The power meter (Coherent Radiation Model 201) is placed behind the chopper and/or attenuator. (In the Q-switched mode, the chopper and attenuator were never used.) Brick one is removed and the average power is measured. Then the power meter is removed and brick two is used to obstruct the beam.

4a. When irradiating the thermal paper or the suture, the optical shutter is placed in the system. The shutter cannot withstand long exposures to the beam. Therefore, once the shutter is set at the correct exposure, brick two is removed, the shutter is triggered, and brick two is immediately replaced.

4b. When irradiating the plastic sheets or the corneas, the beam is focused using the procedure described in (a). The shutter is then removed. The desired translation speed is set and the motor is turned on. If a cornea is being irradiated, the argon gas is directed onto the tissue. A photograph of the setup described in this step of the procedure is presented in Figure 14. Brick two is removed until the incision is complete and then the brick is replaced.

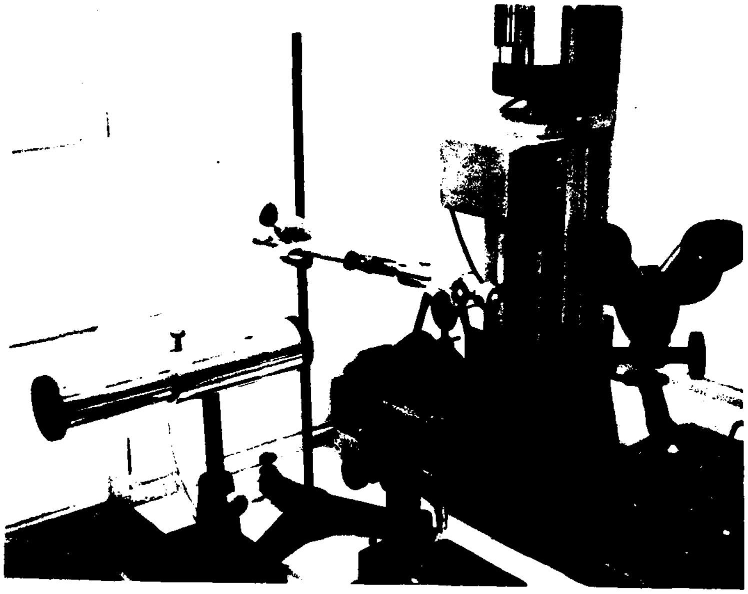

Figure 14. Mounted Eye with Optical Components

5. The resulting hole, in the case of the thermal paper, or width of incision, with the plastic, was measured using a Cenco travelling microscope. The corneas were placed in a preservative and then sent to the Ohio University Eye Clinic for analysis.

V Results and Discussion

The results of the experiment conducted on the thermal paper, plastic sheets, and corneal tissue are discussed in this chapter. The advantages and disadvantages of using the beam expander and the difference in the resulting incisions between continuous wave, externally chopped, and Q-switched modes of operation are also examined.

Irradiation of Thermal Paper

The use of the beam expander substantially reduced the spot size of the laser beam. For the following measurements the beam expander ratio f_2/f_1 was set at 5. The spot diameters (with laser power = 1.0 W) were measured at different exposures with and without the beam expander (Table II). The outer diameter of the charred spot is essentially a measurement of how far the heat energy diffused, while the inner diameter is the size of the hole, and most likely, the size of the beam. Figure 15 is a photograph of three laser spots on the thermal paper, enlarged ten times. The spots represent beam irradiation of 1.0 W power at 1/10, 1/25, and 1/50 second exposures (from left to right on the photograph) without the beam expander. The next photograph (Figure 16) is a laser spot enlarged twenty-five times, with a beam expander in the optical system. It was

TABLE II

Thermal Copying Paper Experiment

Exposure Time (sec)	Without Beam Expander		With Beam Expander	
	Outer Diameter(μm)	Inner Diameter(μm)	Outer Diameter(μm)	Inner Diameter(μm)
1/10	518	251	306	40
1/25	422	227	245	35
1/50	380	186	231	28
1/100	335	216	150	29
1/200	314	152	115	30
1/400	282	158	108	25

made with 1.0 W output power and a 1/25 second exposure (40 m J). The distance between each line on the photograph is 100 μm and 1.0 mm between the numbers. The smallest hole produced without the beam expander was 70 μm in diameter at 0.3 W and 1/400 second. With the use of the beam expander, the smallest hole measured was 25 μm at 1.0 W and 1/400 second. In each case (with and without the beam expander), this hole is reasonably assumed to equal the laser beam spot diameter. The predicted spot diameters, using equations (1) and (5) from Chapter III, are 67.2 μm and 13.4 μm, respectively.

Irradiation of Surgical Suture

A three-centimeter section of 9-0 Ethicon surgical suture was severed with a focused beam formed at a variety of different output powers and shutter exposures. The lowest energy needed to sever the suture was 0.75 m J; that is, a laser power of 0.3 W and an exposure time of 1/400 second (Figure 17). Since the germanium lens did not transmit radiation in the visible portion of the spectrum, an alignment laser could not be used to assist in focusing the CO_2 laser directly onto the suture. Therefore, trial focusing was necessary, leading to the two dots which appear in the vicinity of the broken suture. The third exposure vaporized a section of the suture without marking the

Figure 15. Laser Spots on Thermal Paper Without Beam Expander

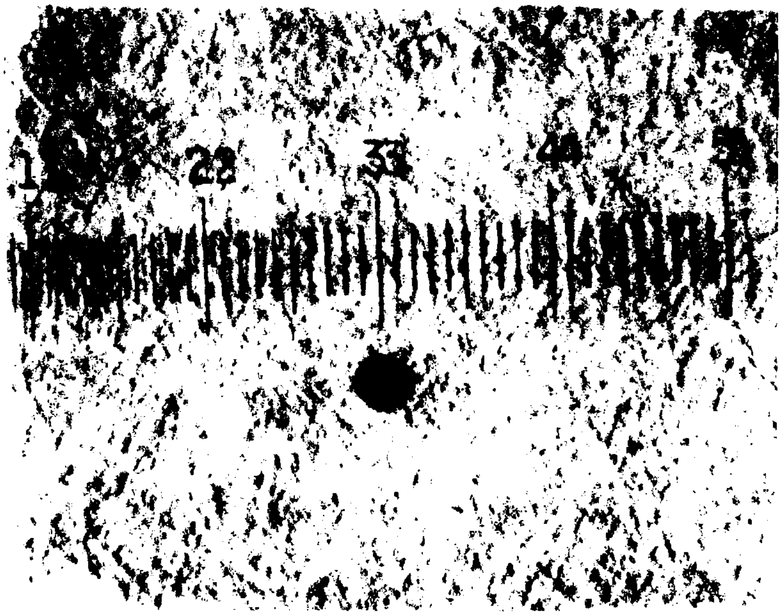

Figure 16. Laser Spot on Thermal Paper With Beam Beam Expander (The center hole may not be apparent in reproductions of this picture)

thermal paper below. In the photograph, the distance between each line is 1.0 mm. This demonstration proves that the laser beam can be precisely controlled.

Irradiation of Plastic Sheets

Irradiation of targets cut from plastic sheets indicated several important findings. First, the externally chopped mode of operation resulted in incisions which had smoother edges and a more uniform vaporization of the plastic than did those incisions made with the laser in the CW mode. As mentioned in Chapter IV, the mechanical chopper reduced the average power passing through it. For example, if 5.0 W continuous power were incident on the 3-slot chopper (which has a 10% dutycycle), then the average power measured just after the beam passed through the chopper wheel would be 0.5 W. The incident power on the 15-slot chopper (50% duty-cycle) was limited to 1.0 W in order to obtain an average power no higher than 0.5 W.

Figure 18, a plot of beam power versus time, illustrates the difference between operating the laser in the CW mode and in the two chopped modes. Each graph represents an equivalent average laser power of 0.5 W. The top graph is for the CW laser, operating continuously at 0.5 W. The middle graph shows the laser beam passing through each slot

Figure 17. Severed Surgical Suture

of the 15-slot chopper for 1/900 second, at a power of 1.0 W, and obstructed by the area between the slots for the same time interval 1/900 second. The bottom graph represents power versus time for the 3-slot chopper. This chopper allows the highest power (5.0 W) to pass through each slot. Here the beam is obstructed for 9/900 second and on for 1/900 second. Whereas the 15-slot chopper passes 1.11 mJ (1.0 W X 1/900 sec) per pulse, the 3-slot chopper passes 5.55 mJ (5.0 W X 1/900 sec).

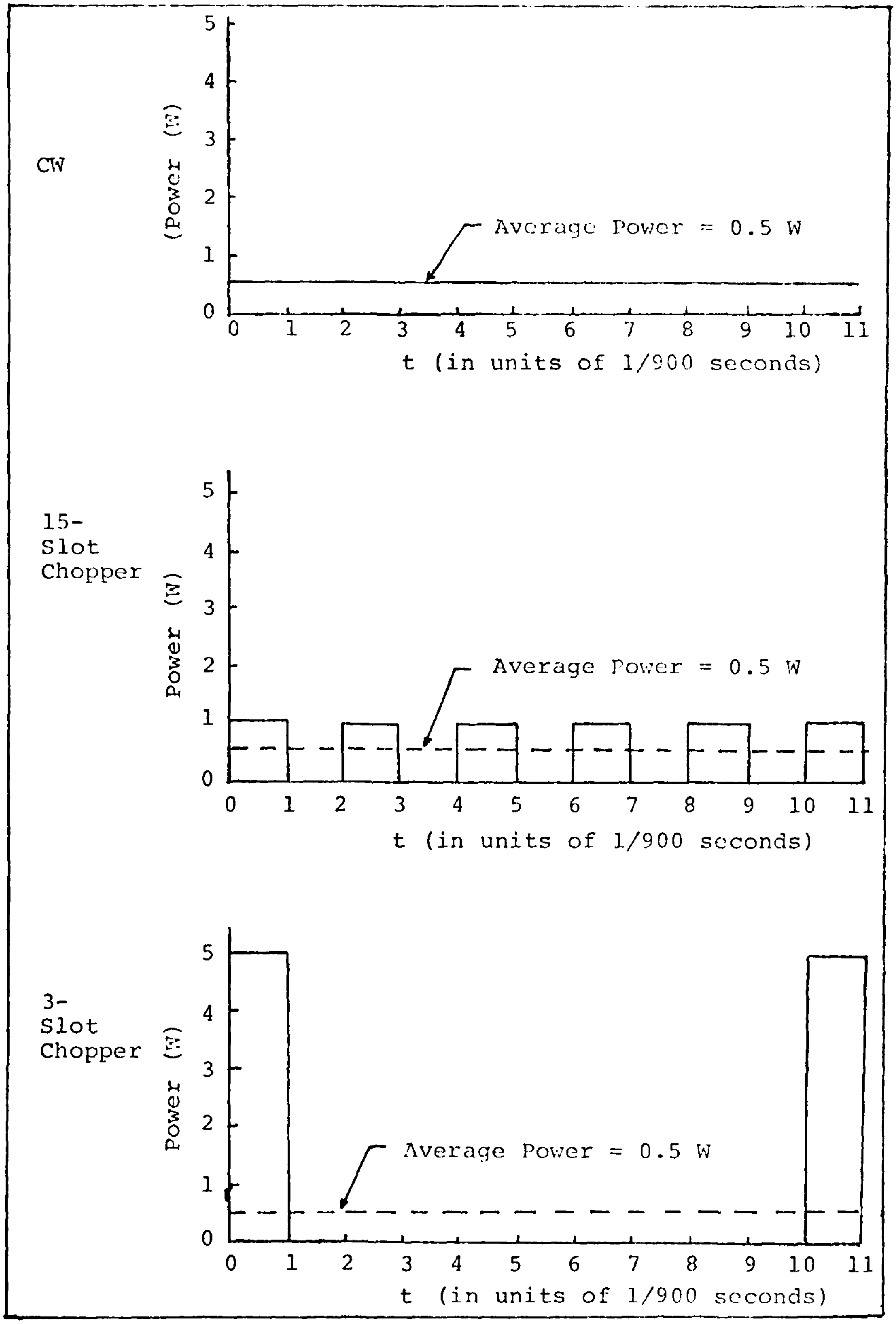

Figure 18. Power vs Time for CW and Pulsed Modes

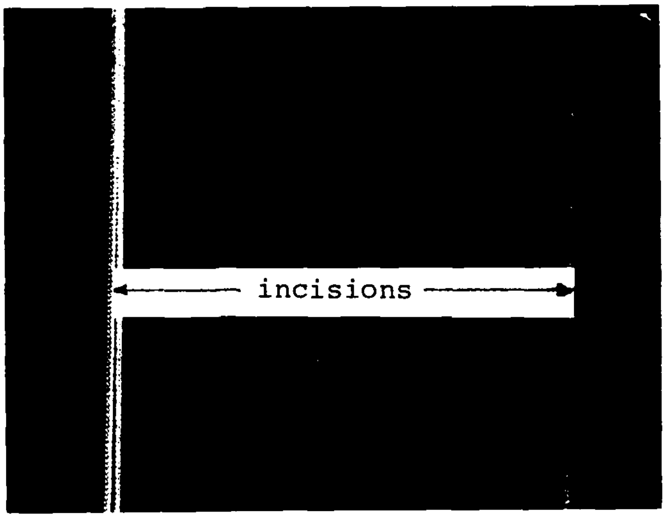

Figure 19. Plastic Sheet Cut With Laser in CW and Pulsed Modes

Figure 19 is a photograph of two incisions made on a plastic sheet. For each incision, the average power incident on the focusing lens was 0.5 W and the sweep speed of the motorized mount was 1.0 cm/sec. The incision on the left was made with the laser beam passing through the 3-slot chopper and the incision on the right was performed operating the laser CW. Under examination, the incision on the left was observed to be more uniform with smoother edges than the incision on the right. On the left incision, the laser vaporized the plastic in a perforated line fashion.

The second important finding from irradiation of the plastic sheets indicated that the width and depth of the incision (at a constant sweep speed) increased as the laser power increased. The width and depth of the incision also increased as the sweep speed of the motorized mount decreased (at a constant laser power). Also, although raising the number of sweeps while maintaining a constant laser power and sweep speed did not significantly expand the width of the incision, it did deepen the incision. These observations indicated that in order to obtain narrow incisions of controllable depth, the laser should be operated in the externally chopped or Q-switched mode of operation. Several consecutive sweeps should then be made to deepen the incision to the desired depth.

Irradiation of Corneal Tissue

The incision on corneas (bovine, hog, and human) followed the same pattern as on the plastic sheets. As previously discussed, the externally chopped mode of laser operation was found to be superior to the CW mode in making incisions in plastic. Therefore, the corneal incisions were made either in the externally chopped mode or Q-switched mode. Four different combinations of arrangements were tested: externally chopped-without beam expander; externally chopped-with beam expander; Q-switched-without beam expander; and Q-switched-with beam expander. The 3-slot chopper wheel was used in the experiments involving the externally chopped mode. The widths and depth of each incision made on the corneal tissue is listed in Table III. These incisions were measured from the histological sections. The recorded widths and depths, as given in the table, are at the point of maximum penetration in the tissue.

Externally Chopped - Without Beam Expander Three incisions were made on a bovine cornea with the laser beam first passing through the chopper and then focused onto the cornea without the use of the beam expander. The power measured after the beam passed the chopper was 0.5 W (5.0 W incident on the chopper). The width and depth of each incision was measured at three different positions: the center of the cornea, position B, and to either side of center, positions A, C (Figure 20). Due to the curvature of the cornea, the laser beam penetrated to different depths at these points. If the corneas were completely flat, every point on the incision should be of the same depth. For example, the first incision was produced by one sweep only, with the focal plane of the laser beam at A and C instead of B. For this irradiation, the laser beam made only a broken incision, that is, a short cut at A and a short cut at C. The incisions at points A and C on the

TABLE III

Incisions on Corneal Tissue

	Average Power (Watts)	Mount Speed (cm/sec)	Number of Sweeps	Width (μm)	Depth (μm)
Externally Chopped					
-- Without Beam Expander	0.5	1.0	1	50	50
	0.5	1.0	5	100	180
	0.5	1.0	20	165	610
Externally Chopped					
-- With Beam Expander	1.0	1.0	20	50	50
	2.0	1.0	1	50	10
	2.0	1.0	20	100	130
Q-Switched					
-- Without Beam Expander	1.6	2.0	20	~70	300
Q-Switched					
-- With Beam Expander	1.6	2.0	30	100	50

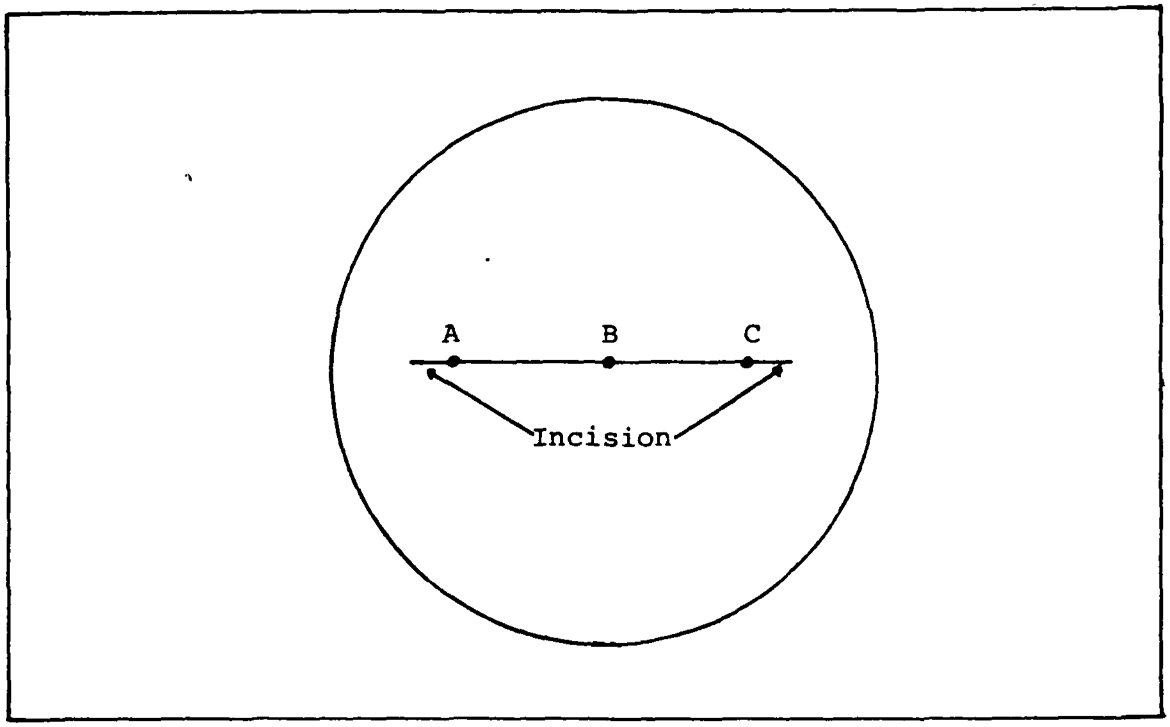

Figure 20. Positions of Corneal Incision Measurements

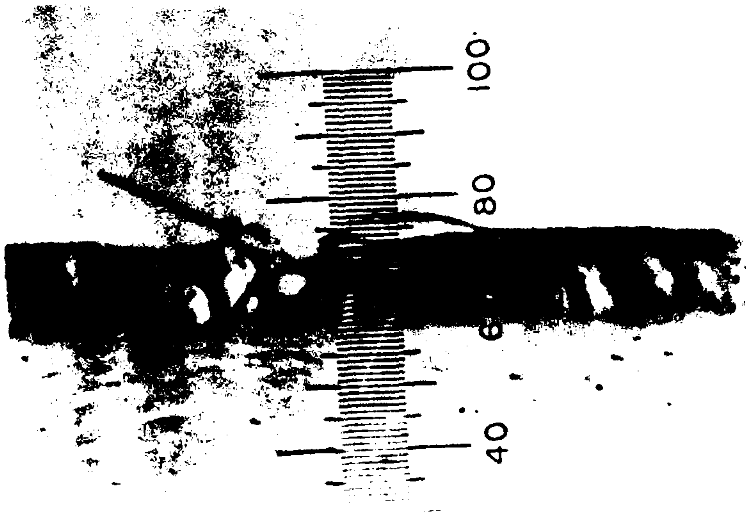

Figure 21. Histological Section of Incision of Bovine Cornea at Edges of Cut (Externally Chopped - Without Beam Expander)

cornea were approximately 50 μm wide and 50 μm deep (Figure 21). On each of the following photographs, the distance between adjacent lines on the accompanying scale is 5 μm.

The second incision (Figure 22) was made with 5 sweeps. The laser was focused at B for this incision. Here, the width of incision was 100 μm and the depth was 180 μm.

The last incision (Figure 23) was produced after 20 consecutive sweeps. Corneal tissue surrounding the incision was charred even though argon gas was flowing over the surface of the cornea during the irradiation. The cut was 210 μm wide and 180 μm deep at the edges (points A and C) and 165 μm wide and 610 μm deep at point B (Figure 24). The depth of this incision is greater than the required depth of most corneal incisions on humans since the human cornea is 750 μm at its thickest point.

Externally Chopped - With Beam Expander With the beam expander properly aligned and set at the 5:1 expansion ratio, incisions were made on hog corneas with the laser beam externally chopped. The same positions shown in Figure 20 were points of measurement on the histological sections of these incisions. On one cornea, two incisions were made with 2.0 W output power (20 W incident on the chopper). The first incision was made with only one sweep. A slight penetration of the tissue, 10 μm deep, was barely evident.

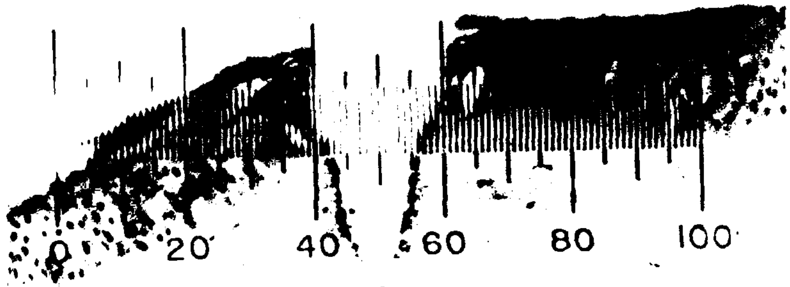

Figure 22. Histological Section of Incision of Bovine Cornea at Center of Cut (Externally Chopped - Without Beam Expander)

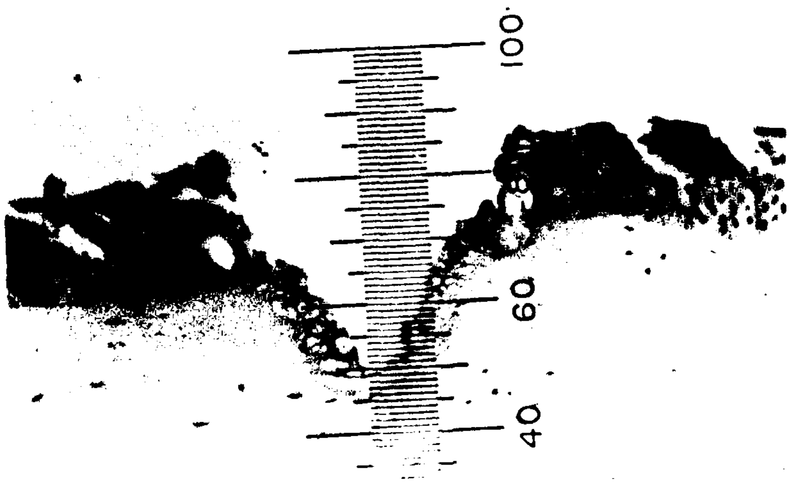

Figure 23. Histological Section of Incision of Bovine Cornea at Edges of Cut (Externally Chopped - Without Beam Expander)

Figure 24. Histological Section of Incision of Bovine Cornea at Center of Cut (Externally Chopped - Without Beam Expander)

This very slight penetration was attributed to a misalignment between the focal plane of the beam and the surface of the cornea. The second incision, after 20 consecutive sweeps was measured to be 100 μm wide and 130 μm deep at point B (Figure 25). The depth of the incision diminished to less than 10 μm at the edges (points A and C). Some charring of the corneal tissue occurred at the epithelium.

Only one incision was made on the second hog cornea. The speed remained the same (1.0 cm/sec) but the average output power was decreased to 1.0 W. Twenty sweeps produced

Figure 25. Histological Section of Incision of Hog Cornea at Center of Cut (Externally Chopped - With Beam Expander)

an incision (Figure 26) approximately 50 μm wide and 50 μm deep.

As discussed in Chapter III, the Rayleigh range becomes very short when extremely small spot sizes are focused with the beam expander/lens combination. With a Rayleigh range of only 46 μm, corresponding to a spot diameter of 25 μm, focusing the laser beam on target is very difficult. Several hog corneas were irradiated when the laser beam was not focused exactly on the tissue. The laser irradiance at the point of contact on the tissue was so low (due to the increase in the spot diameter away from the focal plane)

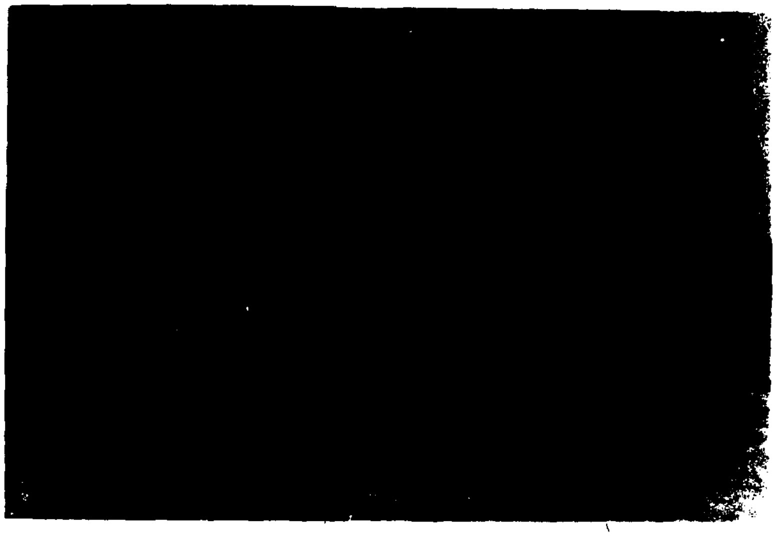

Figure 26. Histological Section of Incision of Hog Cornea at Center of Cut (Externally Chopped - With Beam Expander)

that the laser beam produced only superficial melting of the epithelium. When the plane of corneal tissue was greater than several hundred microns away from the focal plane, the laser beam did not do any observable damage to the cornea.

The major advantage of using the beam expander is to achieve a smaller focused spot and therefore a decrease in the width of the incision. However, the depth of the incision is then limited as a result of the sharply decreased laser irradiance at very small distances away from the focal plane. In order to decrease the width and increase the depth of the incisions, and at the same time reduce the charring of adjacent tissue, the Q-switched mode of operation was tested next.

Q-Switched - Without Beam Expander An incision (Figure 27) was made on a human cornea with the laser in the Q-switched mode and focused without the use of the beam expander. The average power was 1.6 W (peak power was 445 W) and 20 consecutive sweeps were made. The histological section shown in Figure 27 unexplainably closed in the processing procedure. However, the incision was observed before the sections were made. This incision was observed to be uniform and contained less charred collagenous material than the "pulsed" incisions.

The reason for the difference in incisions produced by the Q-switched mode and chopped mode is similiar to the one described earlier between the CW and externally chopped beam incisions on the plastic sheets. The high peak power of each Q-switched pulse caused the tissue to vaporize more uniformly than the chopped pulse. Since the pulse duration of the Q-switched pulse is short, there is not enough time for the heat to spread into the surrounding tissue and cause charring.

Q-Switched - With Beam Expander The use of the beam expander was also tested with the laser in the Q-switched mode. An incision (Figure 28) was made on a hog cornea

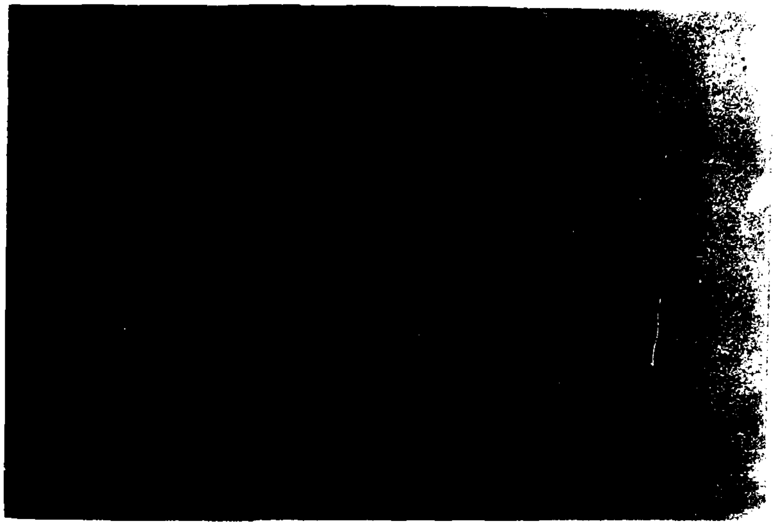

Figure 27. Histological Section of Incision of Human Cornea at Center of Cut (Q-Switched - Without Beam Expander)

Figure 28. Histological Section of Incision of Hog Cornea of Center of Cut (Q-Switched - With Beam Expander)

with the same average laser power (1.6 W) and 30 consecutive sweeps. The depth of this incision was less than that of the incision made under the externally chopped mode with beam expander. Whereas the external chopper passed 11.1 mJ (10 W X 1/900 second) and 22.2 mJ (20 W X 1/900 second) for the incisions on the hog corneas with the beam expander, the Q-switched pulses are only 0.2 mJ (445 W X 500 nanoseconds). The penetration depth would increase if a greater output power in the Q-switched mode were employed. As mentioned previously, the advantage of the very short Q-switched pulses over the longer externally chopped pulses is that there is not enough time for the heat energy to diffuse into the surrounding tissue.

Comparison of Theoretical and Experimental Depth of Incision

The predicted depth of incision, using equation (10) from Chapter III, and the actual depth of incisions differed by an order of magnitude. For example, incisions of least width were made with the laser operating in the Q-switched mode and the laser beam focused after beam expansion. Each Q-switched pulse was characterized by a peak power of 500 W and pulse width of 500 nanoseconds. The beam was focused to a 25 μm spot diameter which resulted in a cross sectional area of 4.91×10^{-6} cm^2. Inserting these values into equation (10) yields the following predicted depth of incision:

$$d = 202\ \mu m$$

Therefore, each Q-switched laser pulse should vaporize the tissue to a depth of 202 μm. However, as shown in the results, in order to obtain an incision of this depth, several consecutive sweeps must be made.

The predicted depth of incision differed from the actual depth for several reasons. The main reason for this difference is due to the "first-order" theory assumption, made in Chapter III, namely that the laser intensity remains constant over the depth of incision. As stated several times previously, the laser beam focused on the surface of the cornea rapidly decreases in irradiance at penetration depth of several tens of microns away from the focal plane. To obtain a more accurate prediction of the depth, the Gaussian shape of the laser beam must be considered and proper beam irradiance at various depths into the corneal tissue used in the calculation.

The other "first-order" theory assumption leading to a difference between measured and predicted values is based on the assertion that the energy loss due to thermal diffusion and radiation is negligible. If this supposition were correct, each incision made without the beam expander should be 70 μm wide and with the beam expander, 25 μm wide.

Clearly, some of the laser energy incident on the cornea must radiate and diffuse into the surrounding corneal tissue.

The remaining "first-order" theory assumptions listed are reasonable. The thermal properties of collagen are different than water. However, since the cornea consists of only 20% collagen, the assumption based on similarity to water is plausible. Absorption of laser energy by the corneal vapor formed when the tissue is vaporized is evidently not a problem since this vapor is removed by the argon gas flow. Also, the reflectivity of the cornea is very low (for water at 10.6 μm it is 0.025 (Ref 33)). Therefore, most of the laser radiation incident on the cornea was absorbed by the corneal tissue, as assumed for the first-order calculations.

VI Conclusions and Recommendations

Conclusions

The precise control of the output power and beam divergence of the CO_2 laser resulted in essentially continuous control of energy deposition on target and focused beam diameters as small as 25 μm. The results indicated that the CO_2 laser can make corneal incisions with a controllable penetration depth of 10 μm and deeper and a width as small as 50 μm.

The optimum mode of laser operation was found to be the Q-switched mode. Less charring of the tissue occurred using the Q-switched mode than with the externally chopped mode. Also, the penetration depth of the incisions made using the Q-switched mode at higher peak output powers could be greater than the depth of those incisions made with the externally chopped beam.

On disadvantage of focusing the laser beam down to such small spot diameters is the creation of a very short Rayleigh range, that is, a very small depth of focus. The surface to be irradiated must remain within approximately 50 μm of the beam's focal plane (for a 25 μm spot diameter) lest the beam irradiance drop too low to vaporize the corneal tissue. Therefore, the need for the laser beam to be focused exactly on the corneal tissue to be vaporized becomes more critical the smaller the spot diameter of the focused beam.

With the accurate beam control demonstration in this study, the laser may supplement and even replace the scalpel in some surgical procedures of the cornea. These procedures include, for example, radial keratotomy, corneal transplants, and rapid and precise cutting of surface sutures.

Recommendations

In the process of accomplishing a successful project, there are many recommendations that can be made for future research. A definitive study is needed on the thermal conduction and local temperature changes in the cornea following laser irradiation. It is necessary to investigate possible thermal damage of the endothelium layer of the cornea before the ophthalomologist uses the laser on living patients.

The difference in the healing processes between an incision made with a laser and one accomplished with a scalpel must be examined on living animals. When an incision is made with a scalpel, the tissue is separated by the scalpel and then closes once the scalpel is removed. Very few cells in tissue are actually destroyed. However, when a laser makes an incision, the tissue is vaporized and a gap remains once the incision is complete. This gap may be only 25 to 50 μm wide but since tissue surrounding the incision is melted, the healing time may be longer than the scalpel incision. Studies are needed to compare healing times.

The next recommendation is to design an integrated system which satisfies the man/machine (surgeon/laser) interface requirements. A CO_2 laser integrated with a standard slit lamp should be a safe and useful tool in surgery of the cornea. The laser should be capable of both CW and Q-switched modes of operation. The optical system should include a series of lenses or one lens and an adjustable beam expander so that the ophthalmologist has a choice of spot diameters. Eventually, the system could be computerized in order to deal with extremely small spot diameters and subsequent short Rayleigh ranges. Such a system may revolutionize current surgical techniques presently used in corneal surgery.

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Appendix

Storage and Preservation of Corneal Tissue

The method used to store enucleated eyes is basically the same whether the eye is bovine, hog, or human. Extreme care must be taken so that the epithelial layer of the cornea is not damaged. Sometimes when an animal eye is removed in an abattoir, a strip of epithelium may be accidently scratched off in the process. The epithelium may also be damaged when several eyes are placed in the same container or after long exposures to air without moisture.

Just after the animal eyes are received from the abattoir, they should be immediately separated and placed individually in a moisture chamber. This chamber consists of a glass jar, a bed of cotton approximately one inch thick, and a steel cage. The eye is placed carefully into the cage and the cotton is irrigated with 0.9% sodium chloride solution until it is damp (not soggy). The cage is then set in the chamber and refrigerated. This method will keep the eye fresh for four days at most.

The human eye-bank eyes are usually enucleated within a few hours of death of the donor and stored in a moisture chamber. They are shipped in a styrofoam container packed in ice. The eye may be fresh or frozen in liquid nitrogen.

If the eye is fresh, it will be ready to use at anytime. However, a frozen eye must defrost slowly. First, it is necessary to remove the frozen bed of cotton in the moisture chamber and replace it with fresh, damp cotton. Then the eye must remain in the refrigerator for 24-48 hours until the eye is soft. If the eye thaws too rapidly, it may be damaged.

A technique used to store only corneal tissue begins by removing the cornea from either the eye of the animal or human with a trephine or corneal scissors. The cornea is then placed in McCarey-Kaufman (M-K) solution, a modified tissue culture medium (Ref 34), which keeps the cornea viable for one week at most. Several corneas may be kept in one jar containing the M-K solution. This solution is originally bright red and turns orange when the tissue begins to deteriorate. A strong odor from the container may also be an unmistakable sign of decay.

Once the eye has been irradiated by the laser, the cornea should be removed immediately. The cornea, removed from the eye or M-K solution, may be preserved in either formalin (obtained from the base hospital) or a buffered solution containing 1.5% glutaraldehyde and 1.0% paraformaldehyde (obtained from the Ohio State University Eye Clinic). The formalin is easier to use since it sets the tissue rapidly and does not need to be refrigerated.

However, if histological sections are taken, the pathologist prefers the glutaraldehyde/paraformaldehyde solution. This solution preserves the epithelium better than formalin and will result in superior sections. The disadvantages of the glutaraldehyde/paraformaldehyde solution are that it must be kept cold and is very expensive.

Vita

William Harold Possel was born 6 July 1957 in Dayton, Ohio. He graduated from Centerville High School in 1975 and entered the University of Cincinnati shortly thereafter, pursuing a degree in Physics. In June 1979 he was commissioned a 2nd Lieutenant in the Air Force upon receipt of his Bachelor of Science degree. Later that month, he entered the School of Engineering, Air Force Institute of Technology, to pursue a Master of Science degree in Engineering Physics. He is a member of Sigma Pi Sigma.

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A CO_2 laser optical system capable of precise control of output power, beam divergence, and spot size was designed to investigate cutting properties of the focused laser beam on corneal tissue. The laser system was tested in three different modes of operation: continuous wave (CW), externally chopped, and Q-switched. The

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system was tested on bovine, hog, and human corneas. The results indicated that the CO_2 laser can make corneal incisions with a controllable penetration depth of 10 μm and deeper and a width as small as 50 μm. With such accurate control, the laser may supplement and even replace the scalpel in some surgical procedures such as radial keratotomy, relaxing incisions following corneal transplants, and rapid and precise cutting of surface sutures. By integrating a CO_2 laser system with a standard slit lamp, the ophthalmologist should have a safe and useful tool in laser surgery of the cornea.

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