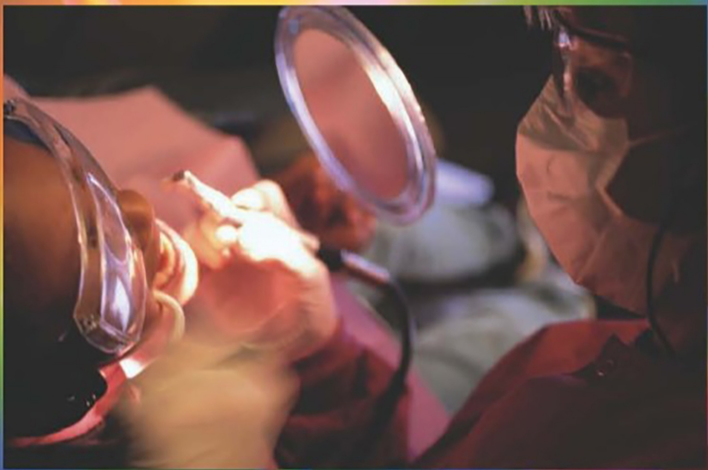
Photonics-Enabled Technologies

Therapeutic Applications of Lasers



OP-TEC

Optics and Photonics Series

Therapeutic Applications of Lasers

Photonics-Enabled Technologies

OPTICS AND PHOTONICS SERIES

OP-TEC: The National Center of Optics and Photonics Education

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PREFACE

This module addresses the role of optics and lasers in the field of biomedicine. OP-TEC treats biomedicine as a *photonics-enabled* technology. The current OP-TEC series on photonics-enabled technologies comprises modules in the areas of manufacturing, biomedicine, forensic science and homeland security, optoelectronics, and environmental monitoring, as listed below. (This list will expand as the OP-TEC series grows. For the most up-to-date list of OP-TEC modules, visit http://www.op-tec.org.)

Manufacturing

Laser Welding and Surface Treatment

Laser Material Removal: Drilling, Cutting, and Marking

Lasers in Testing and Measurement: Alignment Profiling and Position Sensing

Lasers in Testing and Measurement: Interferometric Methods and Nondestructive Testing

Environmental Monitoring

Basics of Spectroscopy

Spectroscopy and Remote Sensing

Spectroscopy and Pollution Monitoring

Biomedicine

Lasers in Medicine and Surgery

Therapeutic Applications of Lasers

Diagnostic Applications of Lasers

Forensic Science and Homeland Security

Lasers in Forensic Science and Homeland Security

Infrared Systems for Homeland Security

Imaging System Performance for Homeland Security Applications

Optoelectronics

Photonics in Nanotechnology

The modules pertaining to each technology can be used collectively as a unit or separately as stand-alone items, as long as prerequisites have been met.

For students who may need assistance with or review of relevant mathematics concepts, a review and study guide entitled *Mathematics for Photonics Education* (available from CORD) is highly recommended.

The original manuscript of this module, *Therapeutic Applications of Lasers,* was prepared by Dr. Fred Seeber and Dr. Raman Kolluri. Formatting and artwork were provided by Mark Whitney and Kathy Kral (CORD).

CONTENTS

Therapeutic Applications of Lasers

INTRODUCTION

Since the discovery of the laser in 1959, lasers have become an indispensable part of many technologies, including surgical and other medical procedures. As laser technology has improved over the years, many new lasers have been discovered with extensive applications in the medical field. Lasers now are available with output wavelengths ranging from deep ultraviolet to far infrared. Lasers whose wavelengths coincide with the absorption wavelengths of human tissue components are used extensively in almost all areas of surgery.

New procedures are being developed around the unique characteristics of laser radiation. Pulsed lasers allow the laser beam to be manipulated and produce very short pulses with different energy densities. This allows surgeons to perform the surgery at specific places without affecting the surrounding areas. This module and the companion module *Diagnostic Applications of Lasers* provide an overview of the uses of lasers in medical and surgical diagnostic and therapeutic applications.

PREREQUISITES

The student should be familiar with the following before attempting to complete this module.

1. High school mathematics through intermediate algebra and the basics of trigonometry
2. CORD's Optics and Photonics Series Course 1, *Fundamentals of Light and Lasers*
3. CORD's Optics and Photonics Series Course 2, *Elements of Photonics*

    Module 2-1: *Operational Characteristics of Lasers*
    Module 2-2: *Specific Laser Types*
    Module 2-3: *Optical Detectors and Human Vision*

OBJECTIVES

Upon completion of this module, the student should be able to do the following:

- Describe the properties of laser radiation and the different lasers and beam delivery methods used in medicine and surgery
- Understand the wavelength regions in which maximum absorption occurs for different tissue components
- Describe how lasers are used for the treatment of vascular lesions, tattoos, hair removal and facial reconstruction
- Measure the absorption coefficient of an organic tissue at different wavelengths
- Understand the structure and absorptive properties of different parts of the human eye
- Explain how *photo thermal, photo disruptive,* and *photo chemical* methods are used in treating eye diseases
- Understand the basics of laser angioplasty, vascular anastomosis, and laser photo chemotherapy
- Describe the basic techniques involved in using lasers to treat gynecological diseases such as CIN and CIS lesions
- Understand how lasers are used in laparoscopy
- Understand how lasers are used in the treatment of soft dental tissues and the removal of hard filling materials from teeth

SCENARIO

Mary Engle recently graduated from a community college photonics program in which she specialized in medical laser applications. She received excellent training on medical lasers and their many applications in medicine and related fields. She learned the theory behind the applications and also spent time learning to work with lasers hands-on. Because of the excellent training she received at the college, Mary is now is capable of working with, maintaining, and troubleshooting all types of medical lasers. She works at a major hospital, assisting an ophthalmic surgeon.

Mary is especially involved in operating argon-krypton and Nd:YAG lasers during surgical procedures. She ensures that the power levels, beam integrities, and pulse characteristics are at appropriate levels. Proper handling of these variables is critical to the success of any surgery in which lasers are used.

When not assisting in surgeries, Mary maintains and troubleshoots the lasers so that they are always ready for use. To keep pace with rapid developments in her field, she maintains frequent contact with laser manufacturers and her former professors. She finds her work exciting and fulfilling. She hopes to develop her skills further and make a long-term contribution in this very important field.

Note on Laboratories

Since the material and procedures covered in the module require special facilities and expensive equipment, no laboratory is provided. Instead, students should work with their instructors to find opportunities for observing the laser-assisted procedures described in the module. After the observations have been made, students should prepare reports that correlate their experiences to the material presented in the text. Completing these reports will require skills comparable to those used in a laboratory.

Medical Lasers

Introduction

The unique characteristics of laser radiation make it well suited to medical applications. Since laser radiation is coherent, its beam divergence is minimal. This means that laser beams can be focused to extremely small dimensions and directed to small areas in precisely defined places without affecting surrounding areas. The monochromaticity of a laser beam allows the user to choose a wavelength that is specifically suitable to the application for which the laser is being used. In the case of argon, dye, and tunable (vibronic) lasers, different wavelengths can be produced by the same laser. The tremendous intensity of laser beams, caused by the fact that laser energy can be concentrated into a single wavelength, makes lasers useful in many applications. In the case of certain lasers that operate in the visible or near-visible wavelengths, the beam can be carried to the location of the application through a fiber optic probe. This makes it more convenient for the doctor and safer for both the doctor and the patient. Pulsed lasers have the distinct advantage of controlling beam characteristics. The pulse width, pulse repetition rate, duty cycle, and intensity can be varied to suit the application. Unlike mechanical instruments, lasers are noncontact and, hence, are much more hygienic and require fewer precautions against infection and other undesirable outcomes.

On the other hand, improper selection of laser parameters can be hazardous. Consequently, laser safety is extremely important in medical applications. Power stabilization is also a problem with certain lasers. In those cases, care must be taken to keep the beam intensity constant during a medical procedure. Laser technicians who operate, maintain, and troubleshoot these systems must be well trained, and their knowledge must be constantly updated.

Properties of laser radiation

Lasers produce radiation that has special characteristics. The following describes these characteristics and explains the operating procedures that generate them.

Coherence—*Laser light is coherent.* This means the light waves produced by a laser move in step; hence, the beam does not diverge as in the case of light produced by other sources such as a light bulb (Figure 1). However, perfect coherence exists only in theory. In real lasers, impurities prevent the light from being perfectly coherent, and a small amount of divergence occurs (Figure 2). The higher the quality of the laser, the smaller is the divergence.

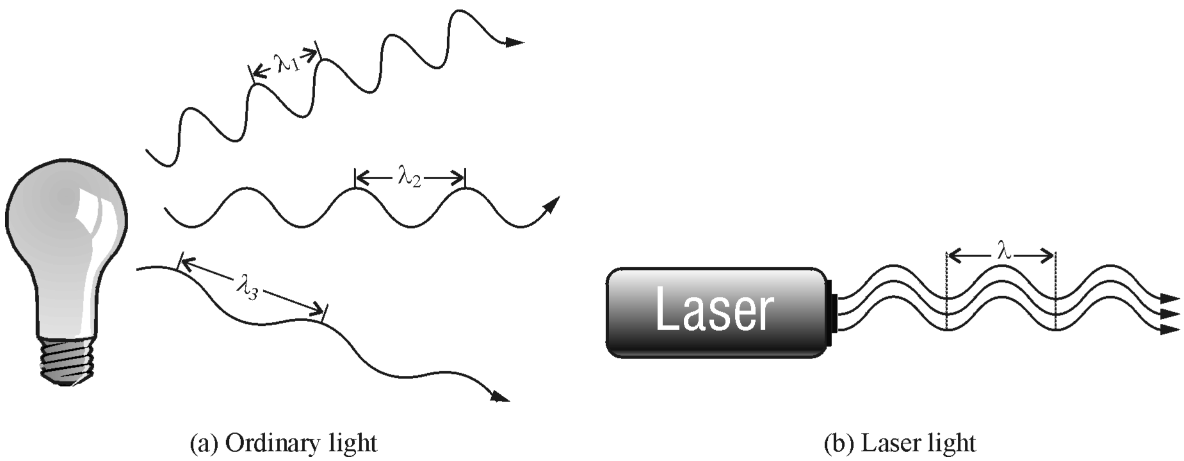

Figure 1 *Comparison of ordinary light and laser light*

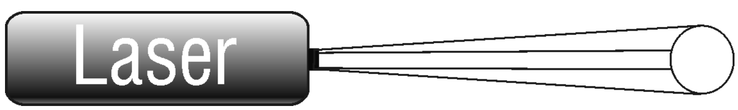

Figure 2 *Beam divergence in a laser beam*

Monochromaticity—*Laser light is monochromatic*. Unlike ordinary light, laser radiation is generated ideally at a single wavelength. In reality, all laser radiation contains a few wavelengths bunched together. This width is associated with longitudinal and transverse modes in the beam and is an indication of the quality of the beam. The smaller the beam width, the better is the quality of the beam.

Energy per wavelength—*Laser light is highly concentrated.* This is one of the most important characteristics of laser light. In ordinary light, the energy is distributed among all wavelengths, making the energy per wavelength very small. Laser light, on the other hand, is concentrated in a few wavelengths, causing the beam be very powerful. The high intensity of laser light is one of the main reasons that laser safety is so important.

Beam diameter and integrity—*A laser beam can be focused to very small diameters.* The intensity of the beam increases as the beam diameter decreases. The following example illustrates this.

The intensity (*irradiance*) is given in units of watts per meter^2:

$$I = \frac{P}{\pi r^2} \text{ for a circular beam}$$

where P is power in watts and r is the radius in meters.

Example 1

If a laser beam with a power of 2 mW and 2 mm diameter is focused to a spot of 3 μm diameter, find the change in intensity.

Solution

Note that radius is half of the diameter.

$$I_1 = \frac{2\times10^{-3}}{\pi(1\times10^{-3})^2} = 636.6 \text{ watts/meter}^2$$

$$I_2 = \frac{2\times10^{-3}}{\pi(1.5\times10^{-6})^2} = 2.82\times10^{8} \text{ watts/meter}^2$$

When the laser beam is focused, its power is increased by more than 5 orders of magnitude. Being able to focus the laser beam into a very small area of treatment is very useful.

Pulsed laser properties

Lasers can be either continuous-wave (CW) or pulsed-wave. Some lasers can be used in both modes of operation, and some can only be operated in one of the modes. In the pulsed mode, light is produced in short bursts with very high intensity. A number of parameters of this pulse are adjustable, giving operators the ability to manipulate the beam to suit their needs. A simple explanation of these parameters is given below.

For ease of understanding, the pulse can be thought of as a triangle. The pulse train will consist of a series of these triangles with the area under each pulse representing its energy (Figure 3).

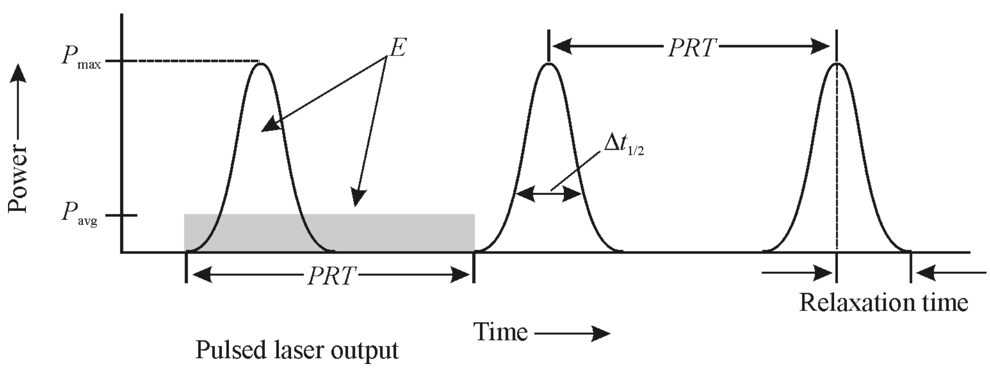

Figure 3 *Average power and pulse repetition time in a pulse train*

The parameters in Figure 3 are defined as

P_{max} = peak power of the pulse

P_{avg} = average power of the pulse over the time interval, *PRT*

$\Delta t_{\frac{1}{2}}$ = width of the pulse at half of the peak height

PRT = pulse repetition time

PRR = pulse repetition rate = 1/(*PRT*)

The energy of a pulse can be calculated using these parameters and the formula for calculating the area of a triangle.

$$\text{Energy} = \text{Area under the pulse} = \frac{1}{2} \times \text{base} \times \text{height}$$

$$\text{base} = 2\,\Delta t_{\frac{1}{2}}$$

$$\text{height} = P_{\text{max}}$$

$$\text{Energy} = \frac{1}{2} \times (2 \times \Delta t_{\frac{1}{2}}) \times P_{\text{max}}$$

The expression simplifies to

$$\text{Energy} = P_{\text{max}} \times \Delta t_{\frac{1}{2}}$$

Using the parameters given above, energy can also be expressed as

$$\text{Energy} = \frac{P_{\text{avg}}}{PRR}$$

Example 2

If the energy of a pulse is 3 mJ, maximum peak power is 1.2 watts, and the average power is 2 mw, calculate the width of pulse at half maximum, *PRT* and *PRR*.

Solution

$$\Delta t_{1/2} = \frac{E}{P_{\text{max}}} = \frac{3\times10^{-3}}{1.2} = 0.0025 \text{ sec} = 2.5 \text{ ms}$$

$$PRT = \frac{E}{P_{\text{avg}}} = \frac{3\times10^{-3}}{2\times10^{-3}} = 1.5 \text{ s}$$

$$PRR = \frac{1}{PRT} = \frac{1}{1.5} = 0.66 \text{ pulses per second}$$

Using suitable techniques, one can adjust almost all these parameters to suit the particular application. For example, pulse duration can be as small as a few femtoseconds (10^{-15} seconds) to a few milliseconds.

Q-switching

This involves an optical shutter that prevents the beam from exiting the laser for a short period while amplification occurs. The shutter is then opened to let a pulse emerge from the laser in a short burst. The process is repeated, causing a series of intense pulses to be emitted. Since mechanical shutters cannot operate at the speeds required by these pulses (micro- to nanoseconds), Q-switches use electro-optical or acousto-optical devices.

Mode locking

The amplification of photons in a laser cavity is achieved by causing the photons to repeatedly reflect between two highly reflective mirrors. Because of the inherent width of a laser beam (caused by photons of slightly different wavelengths), a number of closely spaced longitudinal modes exist in a laser beam. In addition, the differences in phase relation between photons in different portions across the beam diameter will result in multiple transverse modes. These phenomena make the output of a laser beam very complex. By using a suitable aperture in the laser cavity, one can reduce the transverse modes to a single mode (TEM_{00}). However, the longitudinal modes along the length of the cavity continue to compete with each other and reduce overall efficiency. Locking the modes causes them to be in phase so that they reinforce each other rather than compete. A Q-switched and mode-locked laser will produce the most intense pulse train.

Beam Delivery Methods

To be useful in medical procedures, a laser beam must be delivered to a treatment site, which may be either outside or inside the body. This can present a problem, depending on the type of laser and the position of the body. There are four ways in which the beam of a medical laser is delivered to the body: (1) by direct output from the laser resonator, (2) through an articulated arm, (3) through a fiber optic delivery system, and (4) through a hollow waveguide.

Direct delivery

This is the least complicated way to deliver a beam. A laser is simply aimed at the treatment site. Optics may be used to focus the beam at the desired area. This type of system is not useful where a high degree of accuracy is required. Small CO_2 lasers and diode lasers can be used in this way. This method is mostly used in dermatology, dentistry, and hair removal. A particular drawback of this technique is the lack of a visible aiming beam. The position of the affected area must be approximated.

Articulated arms

An articulated arm consists of a series of tubes that are joined by a number of precision bearings (Figure 4) that allow the arm to move in three dimensions. At each of these bearings, front surface mirrors with multiple reflection coatings are positioned such that the beam is carried from the laser to the treatment site. At the end of the flexible arm is a focusing device. These arms are made out of aluminum alloys or carbon-fiber-reinforced composites. The weight of the arms is compensated by counterweights or spring devices. These allow the arms to be very flexible and easy for the surgeon to use.

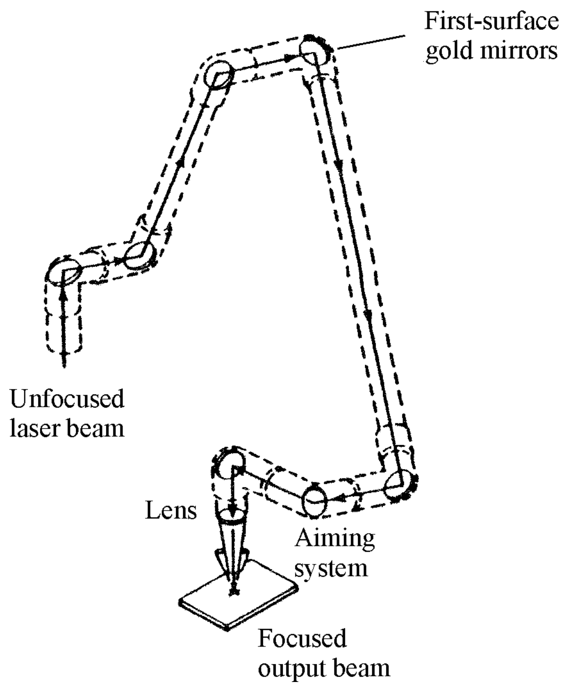

Figure 4 *An Articulated arm and its components*

The main problem with articulated arms is alignment. Some lasers, like the CO_2, operate at a wavelength that will not allow transmission of the beam through a fiber optic cable. This makes the articulated arm a necessity. Low-power visible lasers such as He-Ne and diode lasers are used for alignment. These lasers can guide the CO_2 beam to the target spot by making them follow the same path. Most lasers with articulated arms come with alignment procedures provided by their manufacturers.

Fiber optic delivery system

This method is the most convenient and flexible for the surgeon. Its biggest drawback is that it can be used only for lasers with visible wavelengths. Optical fibers can deliver laser energy to otherwise inaccessible regions inside the body.

Transmission of a laser beam through a fiber is governed by a phenomenon called *total internal reflection.* This occurs when light moves from a medium of higher refractive index to a medium of lower refractive index and the angle of incidence is larger than a specific angle called the *critical angle.* Total internal reflection allows the beam to propagate through the fiber with little loss of power.

For total internal reflection to occur, the angle of incidence at which the beam strikes the core/clad interface must be greater than the critical angle, ϕ_c. In Figure 5, the angle of incidence, ϕ, is greater than the critical angle, ϕ_c. Therefore, total internal reflection occurs.

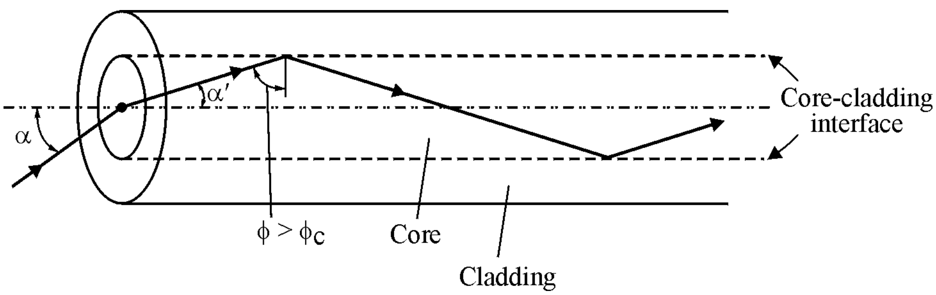

Figure 5 *Transmission of laser beam by total internal reflection in an optical fiber*

An optical fiber consists of a transmitting core such as silicon and is surrounded by a cladding whose refractive index is smaller than that of the core. Thus, if ϕ is greater than the critical angle, a laser beam moving from the transmitting core to the cladding satisfies the criterion for total internal reflection. The relation between critical angle and the respective refractive indices of the core and the cladding is given by the following equation:

$$\phi_c = \sin^{-1}\left(\frac{\eta_{clad}}{\eta_{core}}\right)$$

Example 3

Calculate the critical angle for an optical fiber whose refractive index is 1.55, and the refractive index of the cladding is 1.42.

Solution

$$\phi_c = \sin^{-1}\left(\frac{1.42}{1.55}\right)$$

$$\phi_c = 66.4°$$

This means the beam must be incident on the fiber-cladding interface with an angle of incidence greater than 66.4° for total internal reflection to occur.

Optical fibers used for medical lasers can have diameters ranging from a few tenths of a millimeter to a millimeter. Most of the medical applications require larger-diameter beams as well as strong fibers. A numerical aperture is defined as $NA = \eta_0 \sin(\alpha)$ where η_0 is the refractive index of the medium the beam is in prior to entering the fiber. α is the acceptance angle (Figure 5). Most medical lasers require a large *NA*.

The optical fiber consists of a core, cladding, and a buffer (Figure 6). The core transmits the energy. The cladding, with lower refractive index, allows total internal reflection. The buffer is usually a tough plastic and acts as a cover to prevent damage to the fiber. A fiber with plastic coated silica is called PCS.

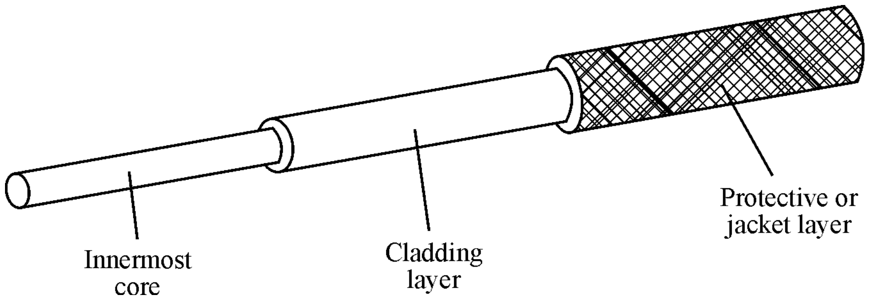

Figure 6 *Components of a fiber optic cable*

Fiber optic probes used in medical applications use both straight and flexible fibers (Figure 7). In flexible fibers, the core fiber is used to deliver energy to cut, coagulate, or ablate the tissue. A second set of fibers transmits a view of the surgical site back to the surgeon.

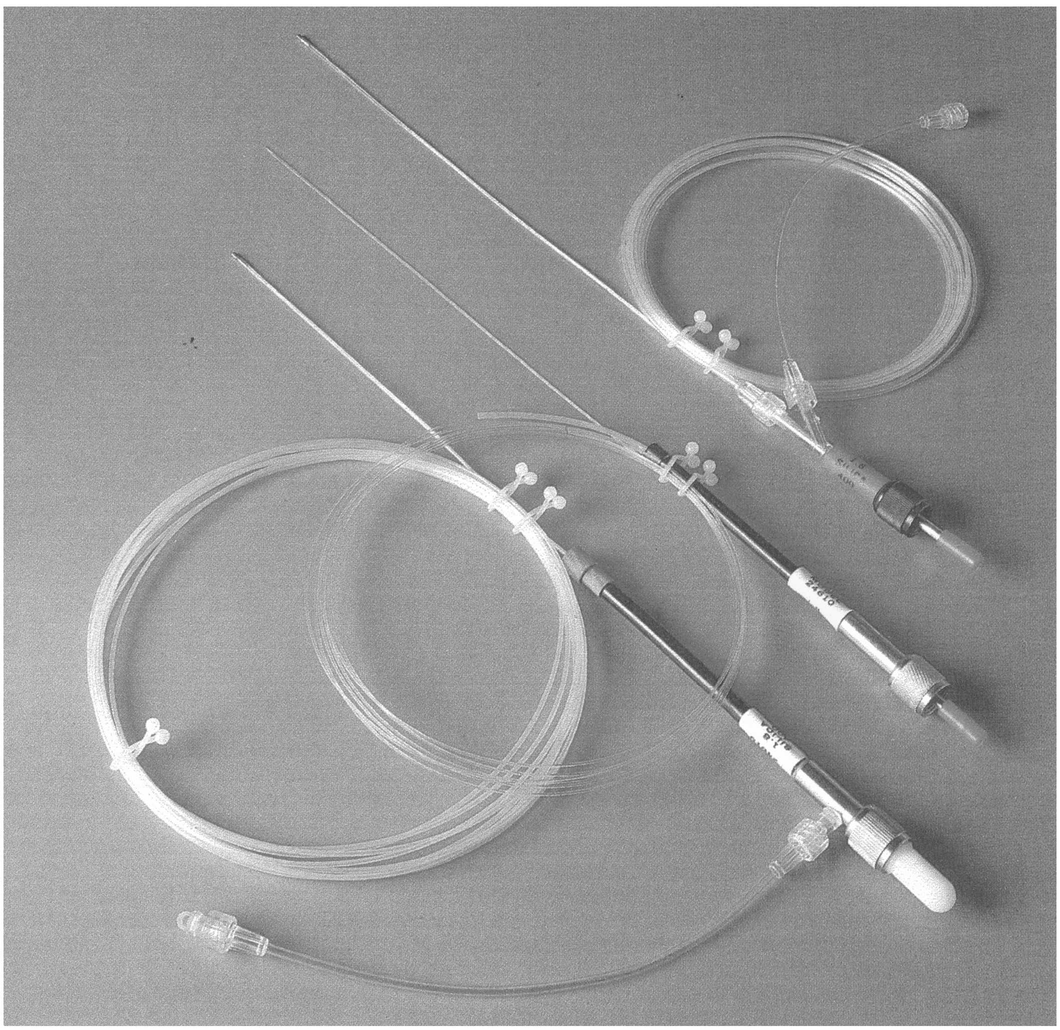

Figure 7 *Optical fibers for flexible delivery systems*

The energy loss that occurs within a fiber is due to several causes. The most obvious is that absorption or scattering takes place inside the fiber. In medical lasers this is not a great issue, since the lengths of the fibers used are small. A second reason is that the beam disperses inside the fiber.

As mentioned earlier, laser beams usually consist of multiple, slightly different wavelengths. Since the angle of reflection is a function of beam divergence, these wavelengths are reflected at different angles. This increases as the number of reflections along the fiber increases. Each reflection causes beam divergence and reduces intensity. Severe bending of the fiber can change the angle of incidence and result in energy loss. Fiber ends cause loss of energy due to refraction at the air/core interface. In short fibers, light will leak from the core into the cladding. This leakage reduces the amount of energy delivered to the surgical site.

Sometimes "cooled" fibers are used in medical applications. This type of fiber has a Teflon sleeve covering the full length of the fiber with a metal ferrule at the *distal* (far) end. At the *proximal* (near) end there is a fitting that can be connected to either an air/gas or liquid source that is used as a purging agent. This purging agent cools the distal end and keeps it clean.

Hollow waveguides

For far infrared wavelengths such as 10.6 μm produced in CO_2 lasers, optical fiber transmission is not possible. In such cases, hollow waveguides are an option. These are essentially hollow, flexible tubes with reflective coatings on the inside. Light is transmitted through total internal reflection by the inner coating. Compared to optical fibers, these waveguides have high transmission losses; their use is restricted to less than a meter. With hollow waveguides, an air purge is used to prevent heat damage to the coatings and to prevent debris from collecting in the waveguide. Hollow waveguides are useful only in noncontact applications. In the case of Er:YAG lasers equipped with hollow waveguides, a sapphire tip is added to allow contact applications such as soft tissue cutting.

Hand pieces

A hand piece is any handheld device that helps direct the beam to the treatment site. It can be as simple as a holder in which to place the end of an optical fiber or as sophisticated as a device consisting of a series of focusing and viewing mechanisms. Hand pieces are designed to be compatible with the wavelengths of the laser being used. In the simplest kind of hand piece, a fiber is held in a rigid tube; the fiber extends beyond the distal end and a clamping device is attached to the proximal end. This allows for adjustment of the fiber length. Hand pieces with short lengths are used in many surgical applications; those with long tips (200–400 mm) are used with rigid endoscopes and laparoscopes.

More complex hand pieces contain series of lenses for focusing the beam. Focusing a pulsed beam creates higher energy densities, which are useful in cutting and ablating tissue in noncontact situations.

In the case of IR beams produced by CO_2 lasers, a single or double lens is used at the end of a hollow tube for focusing the beam. The size of the focused spot is adjusted by moving the hand piece closer to or further away from the target position. One of the main problems encountered when attempting to focus the beam is that the intense heat at the tissue surface generates a plume. This will reduce the intensity of the beam and must be removed by using a purge gas.

Lasers Used in Medicine

Several types of lasers are used in medicine. The choice of the laser, the mode of operation, and the mode of delivery depend on the application. Table 1 shows some of the lasers used, along with their characteristics.

The most commonly used gas lasers are the CO_2, Argon ion (Ar^+), and Excimer (XeCl). Among the solid-state lasers, those having greatest medical application include YAG lasers—Nd:YAG (near IR and frequency doubled), Er:YAG, HO:YAG, and vibronic lasers such as Alexandrite, YLF, and Ti-Sapphire. Ion laser, pumped dye lasers, and diode lasers also have extensive medical applications.

CO_2 laser

This laser can be used in both continuous-wave and pulsed modes. The beam can be focused or defocused. When used in a short-pulse mode, it produces a high-intensity beam, making it useful in applications such as skin resurfacing. CO_2 radiation is highly absorbed by H_2O and can cause damage to the water between the skin cells. It can be used in facial reconstruction and in treating acne scars, chicken pox scars, wrinkles, and *actinic cheditis*. In the defocused mode, the area of interaction is large and the beam intensity is less. In this mode the laser can be used to remove superficial layers of skin without penetrating into deeper areas. Typical applications include removal of wrinkles (facial scars), warts, facial *syringomas*, moles, and *millia*. CO_2 radiation is invisible to the human eye and can be dangerous if not properly monitored.

Nd:YAG laser

This laser emits a 1.06 μm wavelength. It can be frequency-doubled to a wavelength of 532 nm. It can also be Q-switched and mode locked. The 1.06 μm wavelength is used for tattoo removal and dermal pigmented lesions. The frequency-doubled wavelength is used for removal of superficial brown lesions, freckles, solar lentigenes, and red/orange tattoos. Er:YAG lasers have a wavelength of 2.94 μm. In the pulsed mode they can be used for treatment of wrinkles, acne scars, and precancerous lesions. Erbium glass lasers produce 1.540 μm wavelengths and can be used to treat and rejuvenate the skin.

Pulsed dye laser

This is a tunable laser with a wavelength of 500–520 nm. In pulsed mode, hemoglobin absorbs the 577 and 585 nm wavelengths. This laser is used for treating lesions such as port wine stains, nevus flemmus, keloids, and hypertropic scars. Long pulsed dye lasers are also used to treat fine veins and telangiectasia.

Table 1. Medical Lasers and Their Characteristics

LASER	ACTIVE MEDIUM	OUTPUT	WAVELENGTH (μm)	ABSORPTION COEFFICIENT (cm^{-1})	APPLICATION
GASES					
EXCIMER	ArF	Pulsed	0.193	>400	Corneal surgery
	XeCl	Pulsed	0.308	200	Angioplasty, tissue removal
	XeF	Pulsed	0.351	40	
	KrF	Pulsed	0.249	600	
ARGON	Ar	CW	0.488, 0.514	20, 14	Retinal surgery, blood treatment, dentistry
CO_2	CO_2	CW	10.6	600	Cutting and vaporization, dentistry, orthopedics
Helium Neon	He-Ne	CW	0.6328	8	Alignment, biostimulation
Gold vapor	Au	Pulsed	0.6273	8	Tumors
Copper vapor	Cu	Pulsed	0.511	14	Dermatology
LIQUID					
Dye	Rd 6G	CW, pulsed	0.500 to 0.800	4	Retinal coagulation, dermatology
SOLID					
Ruby	$Cr^{3+}Al_2O_3$	Pulsed	0.694	5	Dermatology
Nd:YAG	YAG	CW, pulsed	1.064	4	Eye procedures, cauterization, gynecology, dentistry, ophthalmology, urology, neurosurgery, cardiology
Nd:YAG•KTP	YAG	Pulsed	0.532	12	Eye surgery, multispecialty
Er:YAG	YAG	Pulsed	2.94	2700	Angioplasty
Holmium	Th•AO•Cr YAG	Pulsed	2.14	2500	
Alexandrite				11	Dermatology, tumors
SEMICONDUCTORS					
Diode	GaAs family	CW	0.670 to 1.55	5–10	

Alexandrite laser

This is a solid-state vibronic laser with a tunable range of 700–818 nm. It can be used in pulsed and Q-switched modes. The 755 nm wavelength is absorbed by melanin and is often employed in the removal of tattoos. The rapid-pulsed alexandrite laser removes both tattoos and pigmented lesions. The long-pulsed alexandrite laser can eliminate unwanted hair.

Argon ion laser

Argon and krypton are two gas lasers that produce tunable wavelengths between 400 and 800 nm. The 488 and 514 nm wavelengths of argon are absorbed by hemoglobin and melanin.

These wavelengths are used to treat skin diseases such as *A-V malformations*, *hemangiomas*, fine veins, and *spider nevi*. The 521 and 531 nm wavelengths of krypton are also absorbed by hemoglobin and melanin and thus have similar medical applications.

Diode laser

The GaAs diode laser is a solid-state semiconductor laser producing a wavelength of 810 nm. This is used mostly for the removal of hair. Long-pulsed diode lasers are employed for the removal of hair and also in the treatment of leg veins. These lasers, aided by cooling mechanisms, create less scarring.

Ruby laser

This solid-state laser produces pulses of 694 nm and can be Q-switched. The high-energy pulses can be used to remove tattoos, brown pigment disorders, dilated blue veins, and periorbital pigmentation.

LASERS IN DERMATOLOGY

Introduction

Dermatology is the science that deals with the skin, hair, nails, and sweat glands. Skin protects the inside of living beings from the potentially harmful contaminants and substances that exist all around us. Lasers are used for treating many diseases of the skin. To understand how lasers are used in medicine, one must first understand the basic structure and functions of human skin.

Structure of the Skin

The skin consists of two layers (Figure 8), the surface layer called *epidermis* and the inner layer called *dermis*. The epidermis is approximately 0.1 mm thick.

The outermost layer of the epidermis is called *stratum corneum*. It consists mainly of dead cells. It gives protection against water loss, abrasion, dust, air, and radiant energy. This layer is about 8 to 20 μm thick. Immediately below the stratum corneum there are special cells that produce melanin pigment granules. These granules migrate throughout the epidermis. They help to protect the dermis against ultraviolet radiation and become dark when exposed to it. The change of skin color after sun tanning is due to this process.

The dermis consists of many specialized cells and glands. It also contains connective tissue that gives elasticity and support to the skin. The dermis consists of numerous blood vessels, nerve cells, sweat glands, and hair follicles. The sweat glands regulate temperature through evaporation and cooling of the body. The nerve cells contain heat sensors, pain sensors, and touch sensors (*tactile*). The blood vessels contribute to the maintenance of healthy tissue and heat regulation.

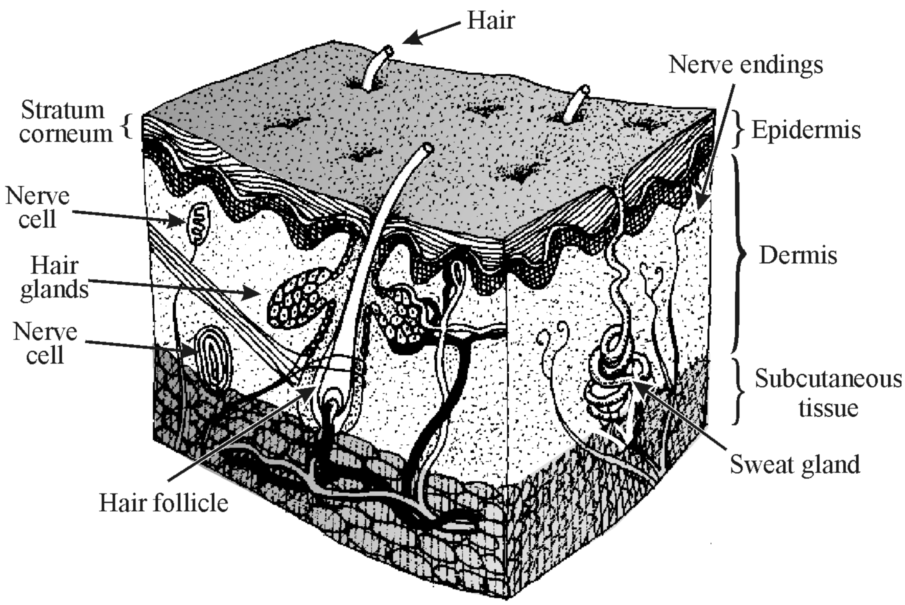

Figure 8 *Anatomy of human skin*

Laser Tissue Interaction

The skin absorbs and reflects the visible portion of the electromagnetic spectrum. It reflects most infrared radiation. The epidermis absorbs most ultraviolet light (100 nm to 315 nm) as well as the 1400 nm to 1 mm range of the infrared region. The skin is less sensitive in the 315–400 nm region. The *melanin granules* of the epidermis absorb most of the ultraviolet light incident upon them and protect the dermis from harmful radiation effects. However, with sufficient intensity, any wavelength of visible, near infrared, or near ultraviolet radiation can penetrate the skin and cause damage.

Laser-induced thermal change to the skin is the most important laser-tissue interaction. When light is incident on a tissue, part of the light will be transmitted, part will be absorbed, and part will be reflected. The reflected light can be a combination of specular and diffused reflections (Figure 9). In medical applications, absorbed radiation has the greatest potential for producing therapeutic effects.

The absorption of laser energy by the tissue is maximum when the absorption frequency of the major component of the tissue coincides with the frequency of the laser beam ($f = \frac{c}{\lambda}$). For example, tissues containing 90 percent water absorb the far infrared wavelength (10.6 μm) of CO_2 lasers whereas tissues with calcium phosphate deposited on them reflect most of this wavelength.

The transmitted intensity by a tissue is given by:

$$I_T = I_i e^{-\alpha x}$$

The transmittance in tissue is defined by:

$$T = \frac{I_t}{I_i}(100\%)$$

where I_T is the transmitted intensity, I_i is the incident intensity, x is the thickness of the tissue, and α is the absorption coefficient (cm^{-1}) of the tissue.

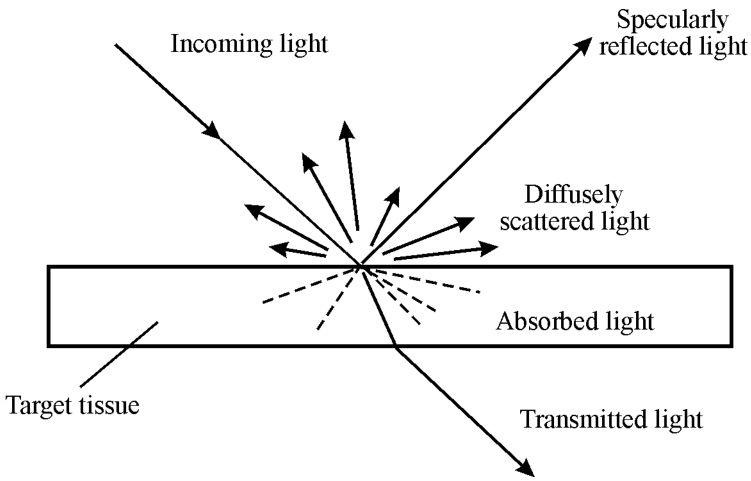

Figure 9 *Reflection, refraction, and absorption of light by a tissue* (The energy absorbed depends on four factors: [1] the wavelength of the incident light, [2] the natural absorption frequency of the tissue, [3] the power density of the beam [joules/cm^2 • sec], and [4] the physical and chemical properties of the tissue.)

Example 4

The absorption coefficient of a tissue sample is 4.0 cm^{-1}. The thickness of the sample is 0.1 cm. Find the transmittance T of the tissue.

Solution

$I_t = I_i e^{-(4 \times 0.1)}$

$I_t = 0.67\ I_i$

$T = 0.67 \times 100\% = 67\%$

Absorption is the reciprocal of reflection. Reflectance of skin as a function of wavelength is shown in Figure 10. Notice that the reflection (and hence the absorption) of fair skin differs from that of heavily pigmented (dark) skin. Where the absorption is very strong, the radiation only penetrates the tissue to a small depth (0.1 to 0.01 mm) relative to the tissue surface. This minimizes the thermal damage to the underlying areas of the tissue.

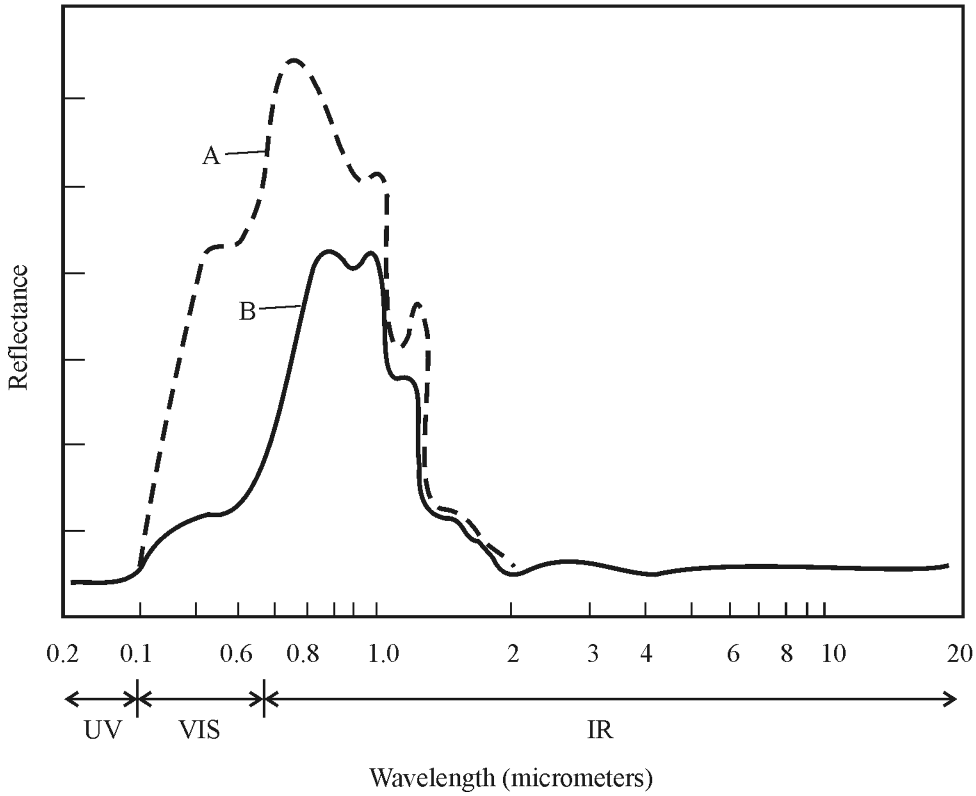

Figure 10 *Reflection of skin as a function of wavelength for (A) fair skin and (B) dark skin*

Table 2 shows the absorption coefficients of water and three biological tissues: skin, liver, and blood.

Table 2. Absorption Coefficients of Water and Different Biological Tissues (cm^{-1})

	Laser Types		
Tissue	**Argon 0.488 μm**	**Nd:YAG 1.06 μm**	**CO_2 10.6 μm**
Water	0.00025	0.363	1106
Skin	55	15	911
Liver	50	12.5	200
Blood	105	9.9	—

Three types of effects occur when radiation interacts with tissue. The first is the *thermal effect.* When infrared wavelengths from lasers such as CO_2, Nd:YAG, Er:YAG, and HO:YAG are incident on tissue, the temperature of the target tissue increases rapidly. For this reason, for all tissues in which water and hemoglobin are the predominant components, these lasers are preferred.

The second effect is the *photo chemical effect.* UV absorption can lead to the breaking of atomic bonds in the target material. For example, the bond energy of an organic molecule is of the order of 3 to 4 eV. The ArF Excimer laser's 193 nm wavelength has an energy greater than

5 eV, which is sufficient to break these bonds. In some cases, when the radiation energy is not sufficient to quickly break these bonds, both chemical and thermal effects will take place.

The third effect is *ablation*. In this process, the material vaporizes without going through the liquid phase. This process takes place in three steps: (1) absorption of the energy, (2) breaking of the bonds, and (3) ablation. The ablation can take place following thermal processes or photo chemical processes or both. For example, the 193 nm radiation of the ArF Excimer laser ablates pure organic tissue, making these lasers useful in ophthalmology. Ablation typically occurs when the wavelength of the laser radiation corresponds to a large absorption coefficient in the material. A medical benefit of ablation is that it happens quickly, providing almost instant feedback to medical personnel performing therapeutic procedures.

Table 3 provides a list of lasers used in dermatology, along with information on wavelengths, output modes, absorption characteristics, and applications.

Table 3. Lasers Used in Dermatology

Laser system	Wavelength	Output mode	Absorption characteristic	Application
CO_2	10.6 µm	Pulsed	H_2O	*Focused mode*: acne scars, chicken pox, wrinkles *Defocused mode:* Skin tags, warts, dermatosis papulosa
Nd:YAG	Nd:YAG: 1.06 nm; 532 nm (freq doubled)	Q-switched	Melanin, hemoglobin	Tattoos, brown lesions, freckles
Er:YAG	Er:YAG: 2.940 µm	Q-switched	Melanin, hemoglobin	Wrinkles, scars
	Er:glass: 1.54 µm	Q-switched	Melanin, hemoglobin	Wrinkles, scars
Alexandrite	700–818 nm	Q-switched	Melanin	Tattoos, pigmented lesions
Argon	488 nm, 514 nm	Continuous wave	Melanin, hemoglobin	Malformations
Krypton	568 nm	Continuous wave	Melanin, hemoglobin	Fine veins, spider veins
GaAlAs	810 nm	Pulsed	Melanin	Hair removal, leg veins, tattoos
Ruby	694 nm	Q-switched	Melanin	Tattoos, freckles, blue veins
Dye	500–585 nm	Pulsed	Melanin, hemoglobin	Port wine stains, Nevus flemmus, fine veins

Laser Treatment of Vascular Lesions

Lasers are successfully used to treat a variety of vascular lesions, including superficial vascular malformations, *facial telangiectases*, *pyrogenic granulomas, and diffuse erythema* (port wine stains). Many types of lasers have been tried—pulsed dye, argon, krypton, KTP:YAG, and copper vapor. However, the pulsed dye laser with a wavelength of 585 nm is the laser of choice for treating most vascular lesions because of its clinical efficacy and low risk. All vascular lesions contain endogenous *chromophores*, hemoglobin, and *dioxyhemoglobin*. The pulsed dye laser with 450 µsec pulse width and 5–10 kW of power can be used to treat them.

Visible, individual vessels and skin defects such as *telangiectasia* and diffuse erythema can be treated with almost any pulsed laser with a wavelength range of 500–600 nm (Figure 11). Where individual vessels within the defect require treatment, the beam can be focused to the size of the vessel. In treating these skin defects, the laser is slowly scanned over the lesion.

In the case of diffuse erythema, the laser beam is defocused to a 5–10 mm diameter and used with a single pulse. The pulsed dye laser with short pulse duration produces short impact damage to the skin without scabbing or blistering. Repeated application of the treatment is often necessary. The treatment is more effective in younger people than in older people because the stains in older people tend to become thick and develop nodules. Techniques using multiple wavelengths and longer pulse duration have been successfully used to remove the nodules and the thickness of the stains. The long-pulsed laser beam also results in more uniform blood vessel damage. This reduces postoperative *purpura* (bruising). Dynamic cooling of the skin surface also increases the patient's comfort during the procedure. Vascular malformations associated with smaller, more superficial blood vessels respond better to treatment than deeper, larger vessels. The fading of the stain usually takes 8 to 10 treatments.

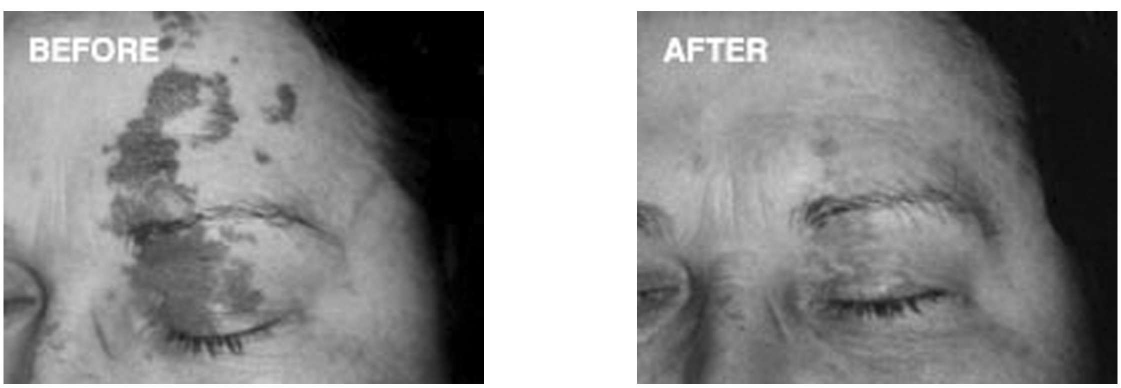

Figure 11 *Removal of diffuse erythema (port wine stains) with Ar+ laser (Dr Sue McCoy, http://www.norseld.com/index.asp?n=13)*

Pigmented Lesions and Tattoos

High-energy, Q-switched, short-pulsed lasers with pulse widths smaller than the relaxation time (time duration between the maximum and minimum values of the pulse; see Figure 3) of the pigment granules (< 5 nsec) are most effective in lightening or eradicating tattoos, *nevi of ota* (a benign pigmentary disorder), birthmarks, freckles, and other pigmented lesions. The *melanosomes* are tiny granules containing melanin inside the pigment cells. These can be removed by Q-switched, short-pulsed lasers. In tattoo removal, different types of lasers are used to remove pigments of different colors to prevent excessive damage to the surrounding skin (Figure 12).

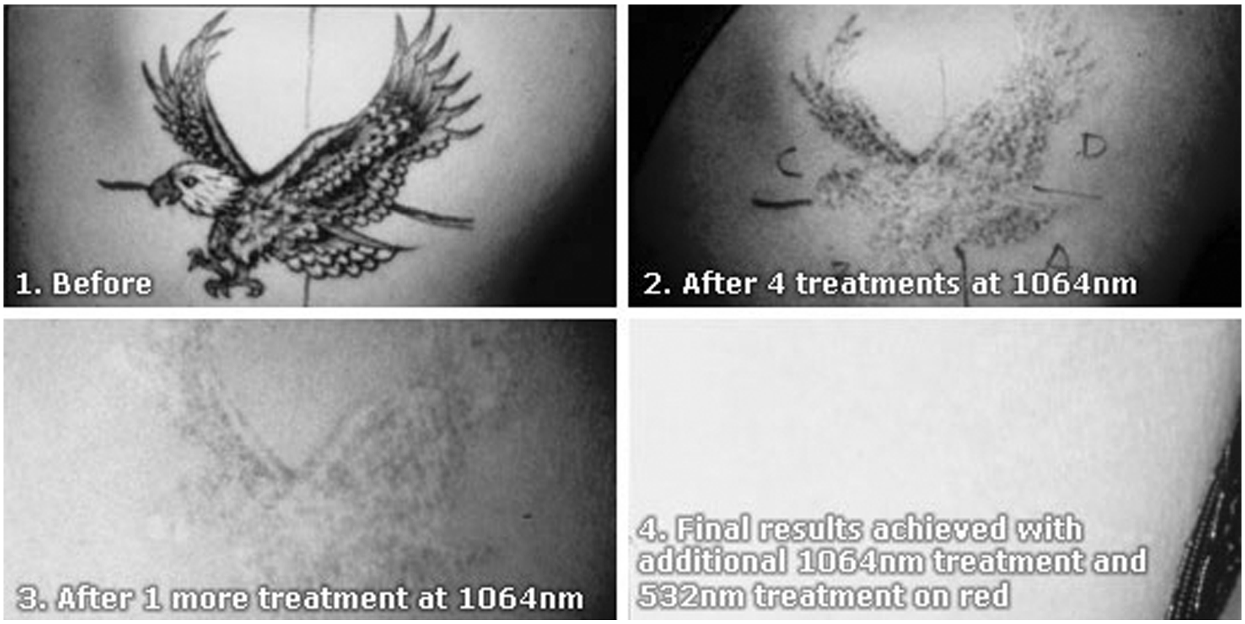

Figure 12 *Laser application in removal of a tattoo (http://www.milfordmd.com/tattooremoval.htm)*

For example, Q-switched ruby, alexandrite, and Nd:YAG lasers are used for removal of black, blue, and green pigments. Q-switched, frequency-doubled YAG, and pulsed dye lasers are used to remove yellow, orange, and red pigments. Superficially located pigments are treatable by shorter-wavelength lasers, while removal of deeper pigment requires longer-wavelength lasers. It is more difficult to remove tattoos from darker skin than lighter skin because permanent *hypopigmentation* and *depigmentation* can occur in darker skin. A pigmented lesion should always be tested for malignancy before subjecting it to laser treatment. Single-color tattoos are much easier to remove than tattoos with multiple, deeply concentrated colors. Some amount of scarring is inevitable in any tattoo removal, but this will heal in time.

Hair Removal Using Lasers

Lasers are used to remove excessive and cosmetically disabling hair caused by *hypertrichosis* and *hirsutism*. The removal is not permanent; the hair will grow back in three or four months. Laser treatments are less painful and much quicker than electrolysis. Superficial burns, pigmentary changes, and scarring may occur during a laser procedure. Figure 13 illustrates the effects of laser hair removal.

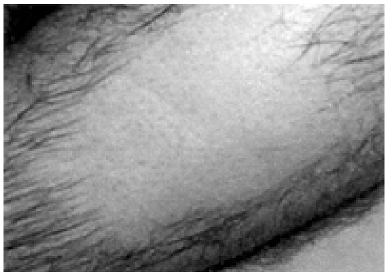

Figure 13 *Removal of unwanted hair using a laser (http/:dermnetnz.org/procedures/lasers.html 5/30/2007)*

Among the lasers used for hair removal are pulsed Nd:YAG, ruby with pulse rates of 270 μs, alexandrite, and GaAlAs diode lasers with 810 nm wavelength. The Nd:YAG laser is often the best choice, as it has the best safety profile and is capable of removing 100 percent of the hair at the treatment site. Also, the replacement hair, which may appear in 3 to 4 months, is much lighter and thinner. Ruby lasers with long pulses can also be effective and create minimal damage to the surrounding collagen. Transient pigment changes without scarring may occur. The use of the alexandrite laser for hair removal is a recent occurrence. Its 755 nm wavelength is effective in removing hair and creates minimal risk to the patient.

Lasers in Treatment of Facial Wrinkles, Scars, and Sun Damage

Pulsed CO_2 and Er:YAG lasers are used to remove facial wrinkles, acne scars, and sun-damaged skin. High-energy pulsed and scanned CO_2 lasers are most often used for this purpose (Figure 14). Side effects reported include postoperative tenderness, redness, swelling, and scarring. However, these side effects are temporary and are mitigated by the replacement skin in a few weeks.

The treatment of darker skin with lasers is not as successful as treatment of lighter skin as permanent loss or variable pigmentation may occur. The Er:YAG laser has the same results and side effects as the CO_2 laser but is much easier to maintain and control. Lasers also are used to vaporize viral warts and destroy dermal blood vessels.

Figure 14 *Facial reconstruction using lasers (Optics and Photonics News, 1998)*

LASERS IN OPHTHALMOLOGY

Introduction

Lasers are used extensively in ophthalmology. In the past, argon, krypton, dye, and Nd:YAG lasers were used. More recently, diode and excimer lasers have been employed. In this section, laser applications in ophthalmology will be discussed.

Structure of the Eye

The main parts of the human eye are shown in Figure 15. The human eye is approximately spherical in shape and measures 24 mm long and 22 mm across. The front portion includes the cornea, which is optically transparent, and the lens, which can adjust its shape to change its focal length. The adjustable iris in front of the lens restricts the amount of light that enters the eye. These components are connected to the tough sclera, which protects the eye and the muscles that move the eye. The eye is filled with two main fluids. The fluid between the cornea and the lens is a watery fluid called *aqueous humor.* It is derived from blood plasma. The liquid that fills the body of the eye is called *vitreous humor*. It is a gel with electrolyte composition and contains protein fibers. The eye lens contains a biconvex and transparent gel. Its shape is altered (to change the focal length) by a group of muscles in the ciliary body.

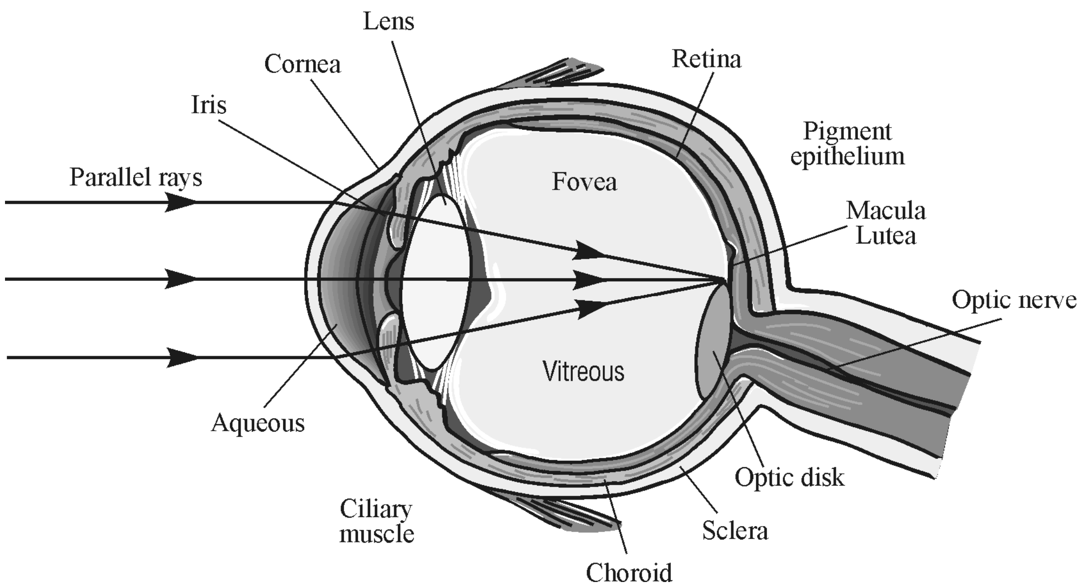

Figure 15 *Schematic diagram of human eye*

When light strikes the eye, part is reflected and part is transmitted. This is due to the differences between the refractive indexes of the air and the cornea. The iris controls the amount of light that goes through the vitreous liquid and is focused on the retina. Interestingly, the eye lens can change its focal length instantaneously and does not normally have either spherical or chromatic aberrations. (Spherical aberration occurs when non-paraxial rays come to a focus at different points. Chromatic aberration occurs when images of different colors do not come to a focus at the same point.)

The absorptive properties of different portions of the eye depend upon the wavelength of light. The retina contains three major pigments—*melanin, hemoglobin,* and *macular xanthophyll*. These absorb visible light from 400 to 1000 nm. The retina has numerous layers. One layer consists of a number of rods and cones. The other layers consist of four types of neurons—*bipolar, ganglion, horizontal,* and *amacrine cells.* The rods and cones, coupled with the neurons, act as the receptors, converting the light energy into electro-mechanical pulses and passing it on to the optic nerve. The cornea consists of several layers of different thicknesses (Figure 16). Most of the cells in all the layers are renewable except those in the endothelium. Surgical procedures require extreme care to ensure that these cells are not destroyed.

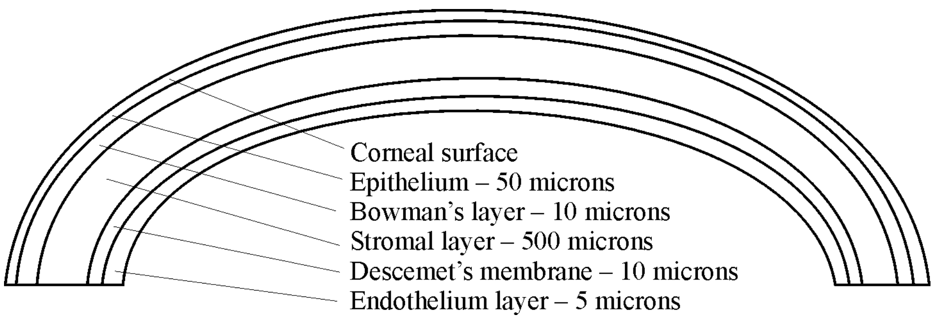

Figure 16 *Schematic diagram of layers that make up the cornea of the eye*

The transmission characteristics of different portions of the eye are shown in Figure 17. The transmission of the eye lens decreases at lower wavelengths (400–600 nm) as a person becomes older.

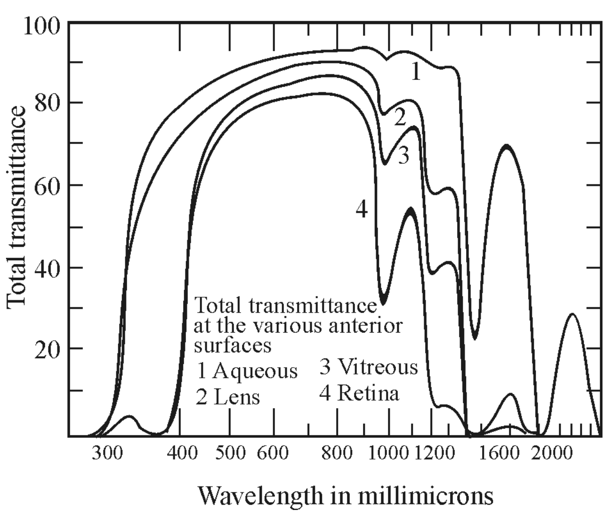

Figure 17 *Transmission characteristics of the human eye*

The optic nerve carries information from the eye to the brain. The retinal layers are tightly sealed and do not allow leakage of blood or protein fluid into the surrounding retina. However, in persons with diabetes and other vascular diseases, the blood vessels become brittle and allow fluid leakage into the posterior region. This causes retinal dysfunction and loss of vision. Also, sometimes fragile blood vessels grow on the surface of the retina and cause leakage of fluid into the eye.

When viewed through a fundus camera, the central optic disc and the connecting blood vessels can be seen (Figure 18). (A fundus camera is a low-power microscope designed to photograph the interior of the eye.) The size of this disc depends on the individual's sex and race. The area called the *fovea* (near the optic disc) contains the maximum number of photoreceptors. In any laser application to the eye, this is the area that requires the most protection. Destruction of the fovea can lead to loss of vision or blindness. The blood vessel network and the fovea are called the *arcades*.

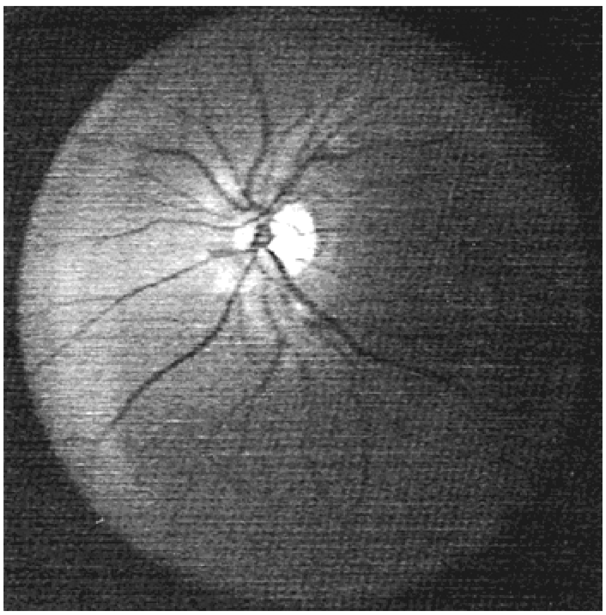

Figure 18 *The visible retinal surface and blood vessels (Vij and Mahesh 2002)*

Optical Properties of the Eye

The focal length of the eye is approximately 16.7 mm. Measured in diopters ($\frac{1}{f}$, where f is in meters), this corresponds to 59.88 diopters. Approximately two thirds of this (44 diopters) is due to the curvature of the cornea, and one third is due to the lens. In other words, the eye behaves like a double lens combination. A small change in the curvature of the cornea can result in a large change in focal length. When people are less than 50 years of age, focusing on nearby objects is not difficult. The lens can adjust its shape to provide the required focal length. At later ages, this becomes more difficult. For people with perfect vision, the combination of cornea and lens focuses the object exactly on the fovea, which has the highest density of receptors. However, for nearsighted (*myopic*) eyes, the focal length of the combination is too short (optical power in terms of diopters becomes large) and the image is focused in front of the fovea. For farsighted (*hyperopic*) eyes, the image is formed behind the retina (Figure 19).

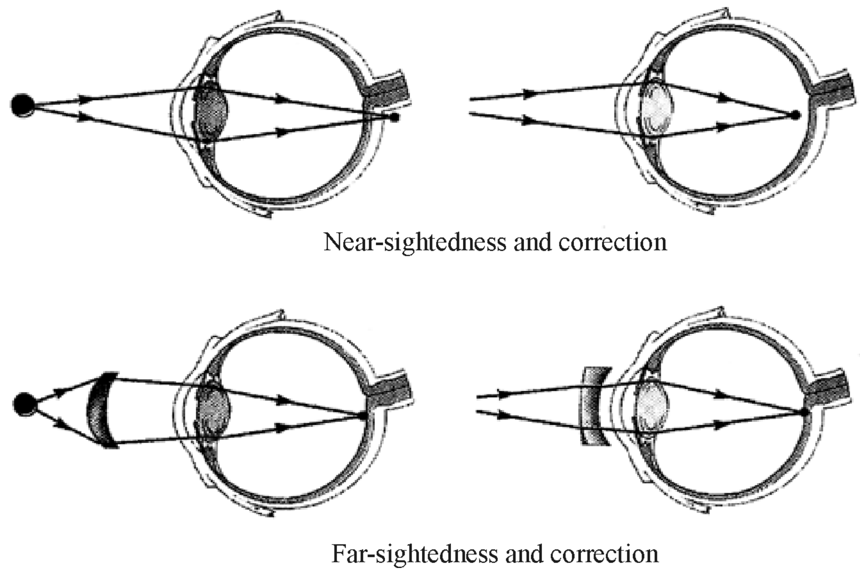

Figure 19 *Schematic diagram showing near-sighted (myopic) and far-sighted (hyperopic) eyes and their corrections*

Laser Therapeutic Applications

Three major techniques are used in therapeutic applications of lasers in ophthalmology: (1) photo thermal applications, (2) photo disruptive applications, and (3) photo chemical applications.

Photo thermal applications

In this technique, the laser wavelength and the absorption properties of the tissue must be matched. The wavelength of the laser, the absorption coefficient of the tissue at that wavelength, the intensity, and the time duration of the interaction decide the nature of the photo thermal effect that takes place. The laser energy absorbed by the tissue is converted into heat. The nature of damage to the tissue depends on both the increase in temperature and the time taken by the temperature rise. A small increase in temperature (5–10° C) over a relatively long period of time (a few minutes) causes cell damage without damaging the cell structure. A larger increase in temperature (20–25° C) over a shorter period of time (less than a minute) causes cellular death (photocoagulation) and structural damage. Increasingly shorter time and higher heating causes the tissue to reach the boiling point and explosively vaporize (photo vaporization). To reduce the damage to surrounding regions, Q-switched lasers of pulse duration less than 100 ns are often used.

Photocoagulation of the retinal tissue—Photocoagulation is the technique used by surgeons to cauterize blood vessels. Cauterization results from the heat generated by a laser beam. This is the most widely used technique in the treatment of diabetic macular edema (leakage of blood into the retina). In the early years, ruby and krypton lasers were used with some degree of success. More recently, argon (514 nm), krypton (647 nm), and dye lasers (577 nm) are successfully used. Tunable dye lasers and the more recently developed solid-state vibronic lasers give the surgeon the flexibility to select the wavelength that is most absorbed by the tissue. For example, the krypton 514 nm wavelength is strongly absorbed by the xanthophylls and can therefore be used to cure diabetic macular edema. Macular degeneration of subretinal neovascular membranes, a condition associated with aging, can also be treated with the photocoagulation technique. In most applications, powers of 100 watt/cm^2 with pulse duration ranging from 0.1 to 1.0 second are used. Some side effects in this kind of therapy are noticed. For example, coagulation of peripheral tissues may cause loss of night vision. In most cases, the advantages outweigh the side effects.

Photo thermal treatment of glaucoma—Glaucoma is a group of eye diseases that damage the optic nerve. The damage occurs as a result of elevated pressure of the fluid (aqueous humor) in the eye. This results in gradual visual changes and loss of vision. In the laser treatment of glaucoma, continuous-wave argon or dye lasers with a wavelength of 488 nm are used to drill a small hole in the peripheral iris. This creates an alternative pathway for the aqueous humor. The major pigment in the iris is melanin, which absorbs the 488 nm wavelength of the argon laser. A typical arrangement of glaucoma treatment with a laser is shown in Figure 20. The patient sits with his/her eye illuminated by a halogen illuminator and the laser beam is directed toward the eye. A CCD (charge coupled device) camera and biomicroscope allow the administering of the surgery.

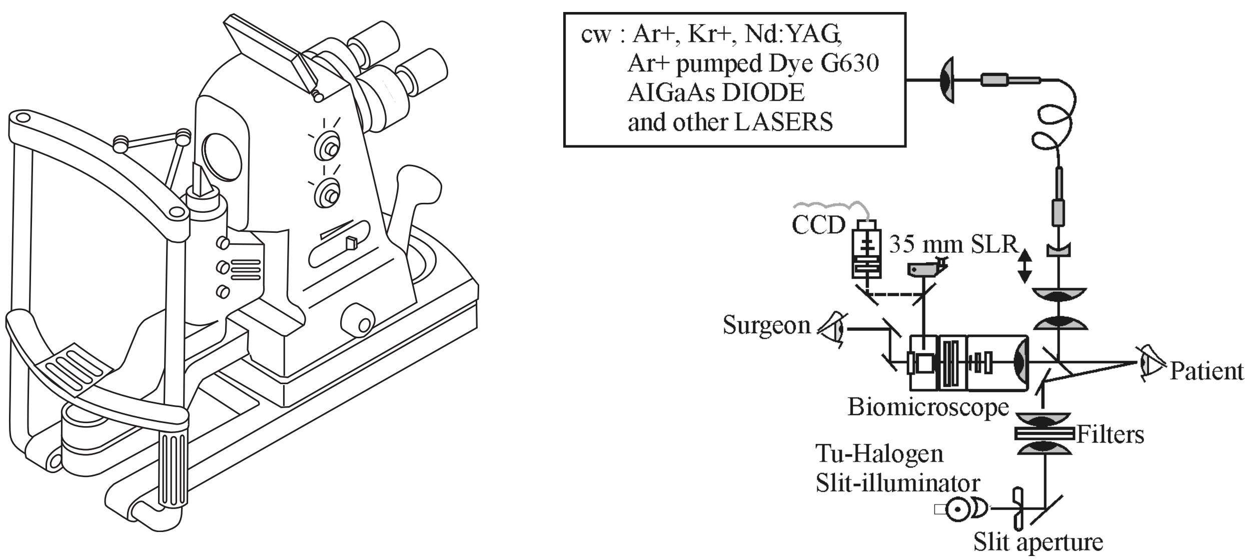

Figure 20 *A drawing and schematic diagram of a laser-assisted delivery system*

Laser corneal surgery—Mid infrared (1.9 μm–10.6 μm) wavelength lasers can be used to cut and weld tissues using photo thermal mechanisms. This is because water, a major component of corneal tissue, strongly absorbs the wavelengths in this region. Manual corneal and refraction surgery is often difficult and requires great skill. CO_2 lasers with a pulse repetition rate of 60–300 Hz, a peak power output of 2.5×10^4 watts, and average power of 150 watts are used. More recently, HF lasers with a 2.7–3.0 μm range at 50–200 nanoseconds and 2.4 J/cm^2 energy are used with much less damage to adjacent corneal tissue than the CO_2 laser. Experiments are now being conducted with Er:YAG laser systems at 2.9 μm, 100 nsec, and 1.5 J/cm^2.

Laser tissue welding—Lasers are used to fuse tissues and bond tissues using biological agents. In addition to ophthalmology, this technique is used in dermatology, urology, neurology, and other areas. In these applications, tissue fusion takes place when laser heating causes denaturation and homogenization of the collagen of individual fibrils. Most of the techniques involve the use of bio-solders to achieve the welding. However, because this technique produces poor welds, more research is being conducted.

Laser cataract surgery—With aging, some portion of the intraocular lens becomes clouded. This is called a cataract. The clouded areas reduce vision and can be treated by removing the clouded portion and replacing it with a plastic lens. Figure 21 shows the procedure used in cataract surgery. The cataractous lens is removed through a small incision with a laser shown in (a). The capsular bag is filled with a fluid with the same refractive index as the original lens which is shown in (c) and (d). The XeCl excimer laser at 308 nm has been successfully used to remove cataracts. However, the fluorescence produced by these pulses causes significant retinal damage. Mid-infrared lasers with a 2–5 μm range have a shorter penetration depth and, hence, minimize the thermal damage. However, mid-infrared wavelengths are difficult to transmit through normal optical fibers. They require infrared-transparent materials such as ZnF_4 and specially designed probes. As already mentioned, delivering the laser beam to the target tissue is always important.

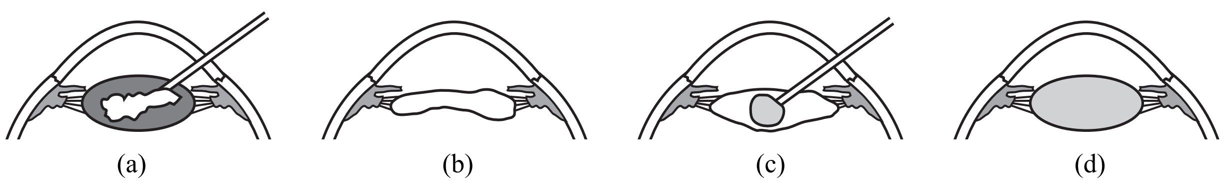

Figure 21 *Schematic diagram of a cataract surgery*

Photo disruptive applications

In this technique, a laser beam is used to ionize the molecules at the target. The radiation beam from a Q-switched Nd:YAG laser (10 nsec) is focused to give a 20–40° cone angle and extremely high irradiance of 10^{10} watt/cm^2. This beam is then focused on the target. The beam will ionize the molecules at the target, thereby creating a plasma. The shock waves caused by the plasma produce mechanical breakdown of structures adjacent to the target site.

One of the most successful applications of photo disruptive techniques is to reduce the opacity of the lens. People who have had cataract surgery often experience fading vision after a few years because the epithelial cells proliferate over time. These cells can be destroyed by using a Q-switched Nd:YAG laser. Nd:YAG lasers are also used for cutting vitreous strands in the vitreous cavity and anterior chamber. The delivery of the high-intensity beam through optical fibers is impossible. Therefore, a series of mirrors positioned in articulated arms is used.

Photo chemical applications

An Excimer laser can produce *photo ablation*. This takes place when short laser pulses from an Excimer laser are focused on a small area of the target tissue. The extremely rapid heating caused by the absorption of radiation by tissue leads to vaporization. When the laser wavelength is carefully matched to the absorption wavelength of the tissue, precise control of the depth of interaction can be attained. Both argon fluoride (193 nm) Excimer lasers and mid-infrared (2.94 μm) Er:YAG lasers are used for photo ablation.

The cornea has extremely high absorption at 193 nm. The energy from the laser at this wavelength is much higher than the bonds linking the carbon atoms in the cornea. Because of this, the laser can vaporize the bonds. Using this technique, precisely controlled volumes of the corneal tissue can be removed. Typical laser parameters used are depth of ablation (0.1–0.5 μm) and pulse intensity (50–250 mJ/cm^2).

The most common application of photo ablation using an Excimer laser is the sculpting and reshaping of the outer surface of the cornea to correct for refractive errors. One of the disadvantages of the Excimer laser is the low pulse repetition rate (10–20 Hz) and the rectangular beam shape (25 mm × 7 mm). Focusing of the beam to very small areas is difficult.

LASERS IN CARDIOLOGY

Introduction

The human cardiovascular system consists of the heart and a vast network of veins and arteries. The anatomy of the heart is shown in Figure 22. It is divided into four compartments. Blood enters the heart through the right artery. It enters the right ventricle through a one-way valve called the *tricuspid valve*. From here, it is pumped into the left lung through pulmonary arteries for oxygenation. The oxygenated blood from the lungs enters the left atrium through pulmonary veins. The blood then passes through the *mitral valve* into the left ventricle. The left ventricle pumps blood through the aortic valve into the arteries of the entire body. The deoxygenated blood returns to the right atrium and the cycle repeats.

A variety of causes can prevent the flow of blood through the heart. Congenital diseases can cause abnormal thickening (*hypertrophy*) of any part of the heart muscle. In those cases, no external inorganic substance is responsible for the condition. Aging can cause deterioration of the cardiovascular system. In those cases, inorganic crystals mixed with organic tissue material are usually present. Lasers are used in treating both hypertrophy and age-related deterioration.

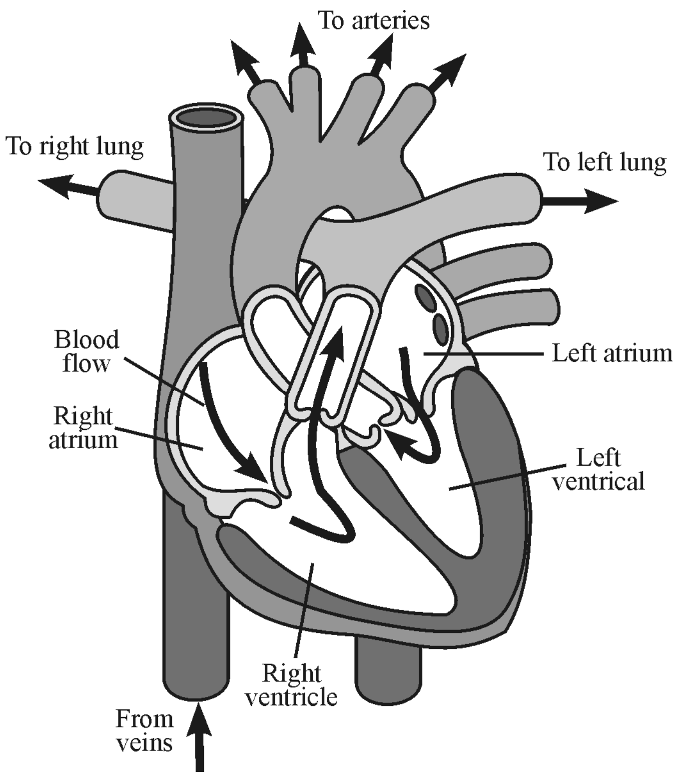

Figure 22 *Schematic diagram of the human heart*

Lasers Used in Cardiovascular Treatment

A number of lasers are used in cardiovascular treatment, including CO_2 (10.6 μm), holmium YAG (2100 nm), Nd:YAG (1060 and 532 nm), argon (351 nm), and Excimer lasers (193, 248, and 532 nm). Some of these lasers and their applications are listed in Table 1.

Atherosclerotic disease is a degenerative disease of the arteries resulting in the deposition of plaque consisting of necrotic cells, lipids, and cholesterol crystals. This results in flow-obstructing lesions that contain both organic tissue and inorganic calcium phosphate crystals. The absorption wavelength of these two materials is very different since the inorganic portion contains less water than the organic tissue.

As stated earlier, the far infrared region is highly absorbed by water. However, delivery of this wavelength through optical fiber is difficult and, hence, has limited application. Nd:YAG lasers are used in thermal angioplasty, and Excimer lasers are used in ablation techniques. The thermal angioplasty has the disadvantage of causing thermal damage to the surrounding tissue and carbonization of the vessel walls.

Lasers in Angioplasty

The technique of removal of plaque deposited in the arteries is called *angioplasty*. This usually takes the form of complete removal of the plaque by using short pulses of an Excimer laser or partial removal of the plaque (using the laser) followed by insertion of a tiny balloon. A thin, flexible catheter consisting of a bundle of optical fibers is introduced into the artery in the groin and then manipulated into the coronary artery where the plaque buildup is located. The fiber bundle is connected to an XeCl Excimer laser (308 nm) with microsecond pulses and power outputs on the order of 100 J/cm^2. These laser pulses are shot through the fiber to ablate the plaque. This procedure is very useful when the artery is completely blocked by plaque. Figure 23 illustrates laser angioplasty. Excimer lasers must be used with great care; the gases used are highly toxic and can be fatal if inhaled. Laser angioplasty is fairly safe and is less expensive than bypass and open heart surgery.

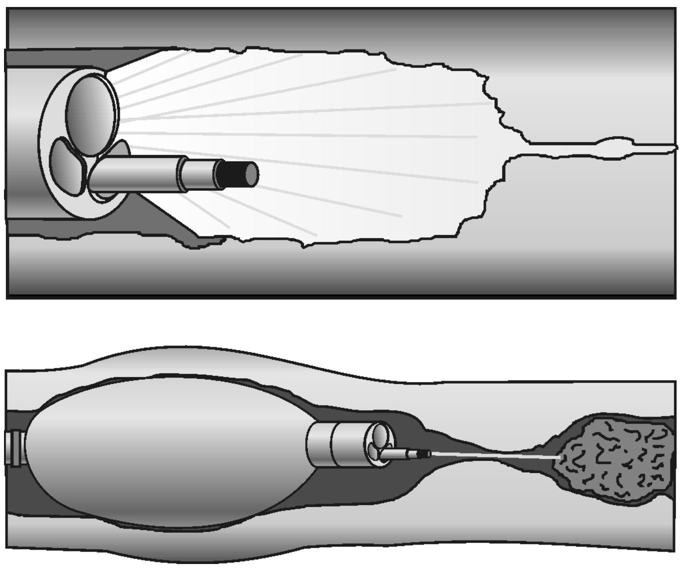

Figure 23 *Plaque removal from arteries using a laser. First the block in the artery is viewed through a fiber optic bundle. Next, the laser is used to ablate the plaque deposit.*

A *thrombus* is a blood clot in the artery; the disease associated with this condition is called *thrombosis*. Lasers can be used to selectively ablate these organic arterial lumps. A thrombus consists of hemoglobin, which is much more laser-energy-absorbent than an artery for the visible region of the electromagnetic spectrum (400–600 nm). As a result, a thrombus can be vaporized through laser ablation. Frequency-doubled Nd:YAG lasers with millisecond pulses have been successfully used in this treatment.

The process involves a catheter consisting of an optical fiber surrounded by a clear liquid that has a higher refractive index than the hollow tube surrounding it. The output of the Nd:YAG laser is directed through the optical fiber, which is directed towards the thrombosis. As the clot absorbs the laser energy, a portion of it is vaporized. This procedure is shown schematically in Figure 24. A vapor bubble is formed; the bubble expands and collapses, causing the clot to further disintegrate. The tip of the catheter is open toward the clot so that blood can flow out through the catheter.

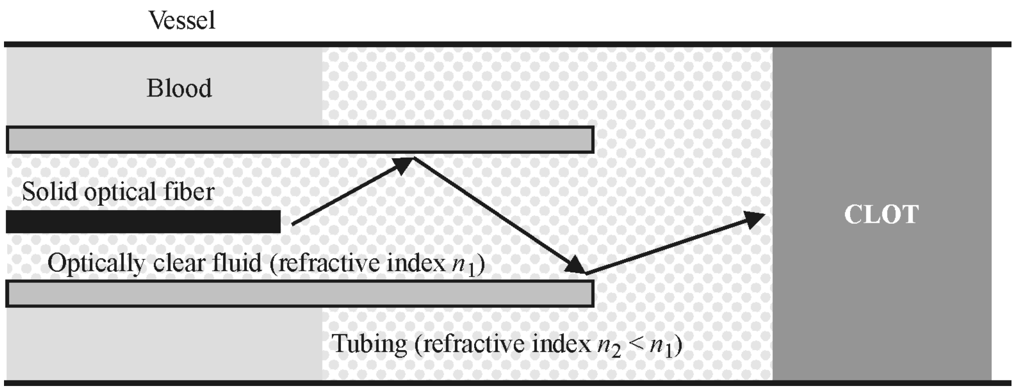

Figure 24 *Schematic diagram showing clearing a blood clot through fluid core catheter*

Vascular Anastomosis

Vascular anastomosis is the welding together of blood vessels. Lasers are useful in this application because they can produce fast welds in human tissues with minimal inflammation. While it is not clear how laser welding in tissues actually takes place, it has been suggested that a combination of photo thermal and photo chemical bonding is responsible. The laser produces heat that causes protein denaturation (structural change) in the target tissue, thus enabling the weld to occur.

Optimal welding occurs when the optical absorption depth of the laser matches the vessel thickness. For small vessels, it is found that a Raman-shifted Nd:YAG laser is suitable. However, this also creates a problem in that different wavelengths must be used for valves of different thicknesses. Computer-controlled laser welding and less expensive diode lasers are being tried to improve the effectiveness of this process.

Fibrogen and other protein solders have also proven to provide stronger welds. The technique of welding is shown schematically in Figure 25. Of particular interest in this area are the 808 nm dye and semiconductor lasers. Since this wavelength coincides with the large absorption window of vascular tissues, better welds are obtained with these lasers. To make better welds, special dyes such as indocyanine dye are sometimes used during the welding process. Development of multicomponent glues with protein bases and customized energy-absorbing dyes would allow these glues to be individually designed for specific welding applications. It becomes a simple matter of matching the absorption coefficient of the dye to the output frequency of the laser.

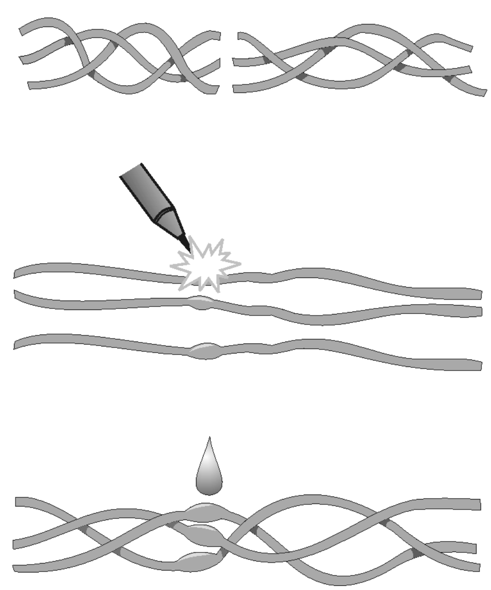

Figure 25 *Schematic diagram showing Ar^+ laser tissue fusion*

Laser Photo Chemotherapy

Restenosis (blockage) stems from any of several causes. One is tissue proliferation caused by inflammation around angioplasty sites. One of the procedures used to decrease this blockage is to insert a metal mesh (stint) against the wall of the artery, revascularizing the artery.

In recent times, photo dynamic therapy (PDT) has been effectively used to destroy targeted tissues in the arteries. In balloon angioplasty, veins and synthetic vascular grafts experience a thickening of the blood vessels called *intimal hyperplasia (IT)*. IT triggers restenosis. PDT can completely eradicate the cells in the vessel walls. Normally, only minimal repopulation occurs after the procedure. PDT alters the vascular wall matrix and inhibits invasive cell migration.

The PDT process consists of injecting a suitable drug such as Photofrin1 into the diseased area via a catheter. The drug is then irradiated by a laser of suitable wavelength. If oxygen is added during the irradiation, cells will be destroyed.

Photoangioplasty inhibits restenosis and is a fairly safe procedure. Diode lasers with 630 nm wavelengths are most often used for this purpose. This wavelength is the longest that is capable of activating Photofrin1. Thus, it causes the deepest penetration into the tissue (3 to 8 mm). Both the laser beam and the illumination beam are transmitted through fiber optic catheters. Different types of lens tips are used for focusing or defocusing the beam to suit the target size. Argon laser pumped dye laser (APDL) systems and Excimer laser pumped dye laser systems are being developed for this purpose.

Transmyocardial Laser Revascularization (TMLR)

Like any other tissue or organ of the body, the heart requires a constant supply of oxygen-rich blood for survival. The heart receives the blood from the coronary arteries. In patients with *coronary artery disease* (CAD), the arteries are clogged and can no longer deliver enough blood to the heart. *Ischemia* is a general term that refers to an insufficient supply of oxygen to an organ. When the heart muscle does not receive adequate oxygen, the result is the condition called *angina*. Most often, the treatment for angina is *coronary artery bypass surgery*. However, for patients with serious heart disease or those who have already had multiple bypass surgeries, this can be dangerous. TMLR is the preferred procedure for those patients. TMLR cannot cure coronary artery disease, but it can reduce the pain due to angina.

In TMLR surgery, a laser is used to cut tiny channels through the heart muscle and into the lower left chamber (left ventricle), which is the strongest and is the heart's main pumping chamber (Figure 26). These channels stimulate the growth of tiny blood vessels in the heart muscle wall (*angiogenesis*). The new blood vessels bring more blood into the heart muscle. TMLR lasers also destroy some of the nerves that cause pain in the heart muscle.

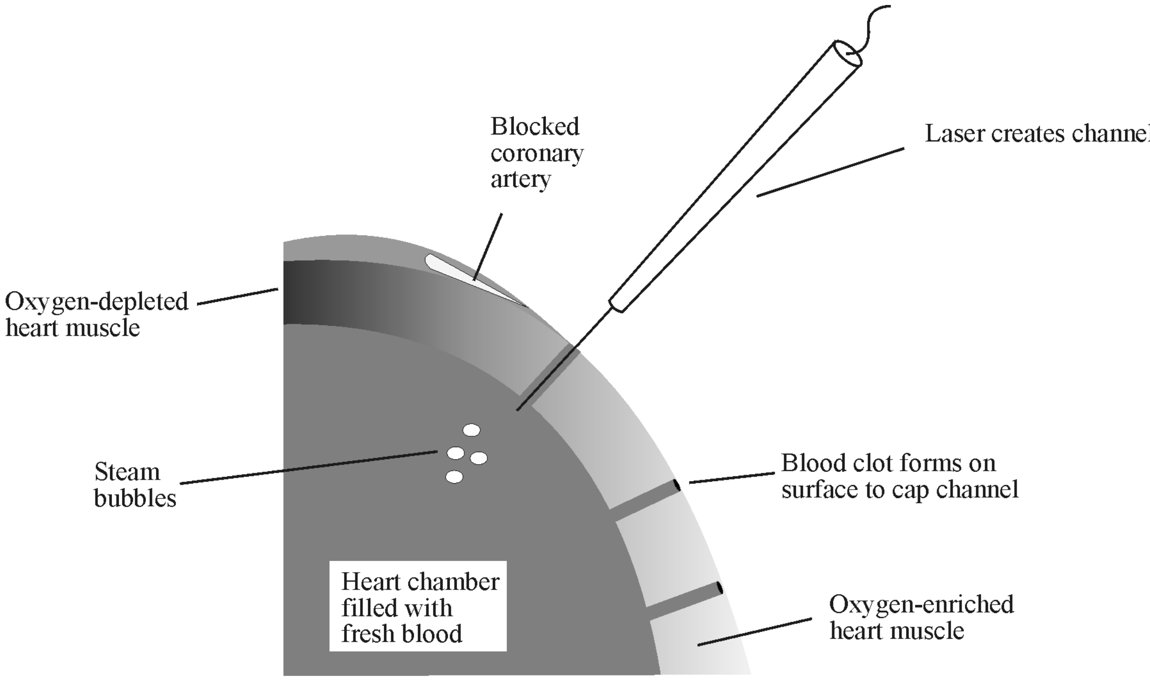

Figure 26 *Schematic diagram showing transmyocardial laser revascularization (TMLR)*

Thulium holmium chromium YAG (THC:YAG) lasers with 2.4 μm output are effective in TMLR. An advantage to using this laser is that its output is in the visible range of the electromagnetic spectrum and thus can be transmitted through optical fibers. An 850 watt CO_2 laser has also been used to drill 15 to 30 one-millimeter channels, causing the "angina" to be significantly reduced. TMLR can be done while the heart is still beating and full of blood. The heart need not be cut open as in open heart surgery, and a heart-lung machine is not required.

Low-Power Laser Use in Cardiology

Red blood cells (erythrocytes) are often damaged when blood is pumped by a heart-lung machine. This is due to the contact of the blood with foreign bodies and the shear stress caused by the blood flow. This process of breaking open the red blood cells and releasing hemoglobin into the surrounding fluid is called *hemolysis*. Hemolysis can be significantly reduced by a low-power HeNe laser. An 8-mW HeNe laser (632.8 nm) can be used to irradiate the blood flow from a distance of 22 mm. This reduces the *erythrocyte deformability* and *erythrocyte ATP* levels.

LASERS IN GYNECOLOGY

Introduction

Lasers are used in a number of procedures in gynecology. While a surgical knife loop electrical excision procedure (LEEP) continues to be used extensively, the use of laser treatments for vaginal and vulvar diseases has grown steadily over the last several years. The CO_2 laser is most often used because of its reduced risk of thermal injury. Since the beam is in the far infrared (10.6 μm), fiber optic transmission poses a problem. The beam must be used along with a low-powered, visible laser so diseased tissue can be targeted. In recent years, waveguide delivery systems have been developed, making it easier to reach targeted tissues. Nd:YAG, frequency-doubled Nd:YAG (KTP), and argon lasers are also used, but less extensively. Nd:YAG lasers are mostly used for deep coagulation.

The CO_2 laser has the further advantage of creating maximum vaporization, minimum lateral scatter, and minimum coagulation. When focused, the beam can be used as a vaporizing tool; when defocused, it can be used for cutting. Typical required power densities are 700–1000 W/cm^2 for cutting and 1000–1200 W/cm^2 for vaporization. The laser can be used both in continuous-wave and pulsed modes. However, the continuous-wave mode is preferred for gynecological procedures.

Laser Treatment of CIN and CIS Lesions

Cervical intraepithelial neopalsia (CIN) is a disorder of the *uterine cervix* (the entrance to the womb). This results in a change of the surface cells that can lead to malignancy if left untreated.

The CIN lesions consist of abnormal cells that actively divide and grow. When a virus called HPV (*human papilloma virus*) infects normal cells, abnormal cells begin to be produced in the transformation zone and a lesion develops. The CIS lesion (*carcinoma in situ*) occurs in the urinary bladder and can be the precursor to bladder cancer.

Both types of lesions are treated with CO_2 lasers. The depth of vaporization required varies from 3 to 7 mm. Higher-power densities (> 1000 W/cm^2) and smaller spot sizes are used in treatment of these lesions. Complications from bleeding or *cervical stenosis* are less frequent when the laser is used in cutting mode (*conization*). To achieve good results with a laser, the entire transformation zone should be treated rather than individual lesions. Figure 27 shows a result of laser treatment of CIN. From left to right the figure shows CIN I, CIN II, and the CO_2 treated lesion.

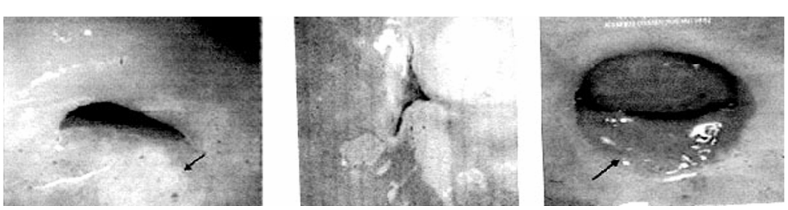

Figure 27 *Treatment of lesions in the lower genital tract using CO_2 laser (Wan 2006)*

Laparoscopy

Endometriosis is a condition that normally occurs in young women. When endometriosis occurs, tissue that looks like the lining of the uterus grows outside of the uterus in the form of tumors, lesions, and nodules. This condition causes severe pain. Most endometriosis is found on or under the ovaries, behind the uterus, or on the bowels or bladder. Laparoscopy is the preferred surgical technique for removing endometriosis (Figure 28). Doctors remove the growths or destroy them with intense heat. Nd:YAG, frequency-doubled Nd:YAG, and argon lasers have been successfully used in laparoscopy. They are able to treat the condition without harming healthy tissue around it.

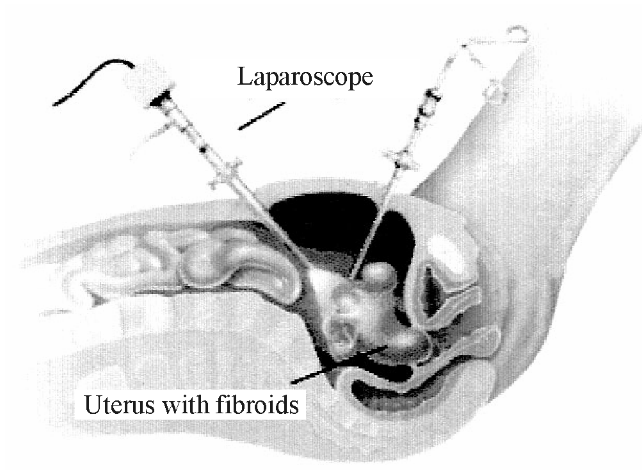

Figure 28 *Schematic diagram showing the removal of Fibroids that are attached to the outside of uterus by a stalk using a laparoscope (http://www.myomectomy.net/)*

Myomectomy, Laparoscopic Myolysis, and Hysterectomy

Uterine fibroids are growths or tumors that develop in the muscular walls of the uterus. Surgical removal of fibroids is called *myomectomy*. Unlike conventional myomectomy, laparoscopic myomectomy uses several small incisions rather than one large incision.

In *laparoscopic myolysis*, multiple punctures are created on the *fibroid* using an Nd:YAG laser. In both cases, a laser with 30 to 50 watts of continuous wave power is used. Laser-induced thermotherapy has also been performed with Nd:YAG and KTP lasers.

Hysterectomy is surgical removal of the uterus. Laser-assisted vaginal hysterectomy (LAVH) is a common type of hysterectomy. It is preferable to conventional electrocautery because the laser cauterizes during the surgery, causing blood loss to be considerably less.

Laser Treatment of Tubal Disease

One of the causes for infertility in women is *tubal disease*. Tubal infertility includes inflammation of the *fallopian tube* and its connection to the *ovary* in a way that affects the transport of the egg, sperm, or embryo. X-rays and laparoscopy provide a way of categorizing different forms of the condition (Figure 29). These categories can be described as (1) *peritubal* or *periovarian* adhesion, (2) distal tubal obstruction, (3) *isthmo-cornual* block, and (4) reversal of sterilization.

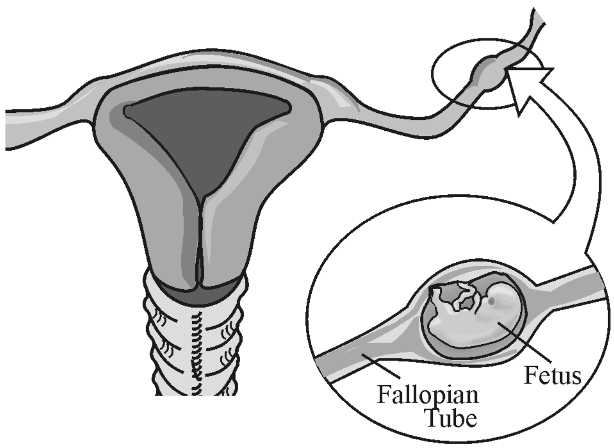

Figure 29 *Schematic diagram showing ectopic pregnancy which can be surgically destroyed using a laser*

In distal tube obstruction, the tube connecting to the ovary is constricted as a result of inflammation or lesions. A laser can be used to vaporize the adhesions between the *fimbria* to create a pathway. This technique is called laser-assisted laparoscopy. Both CO_2 and Nd:YAG lasers have been successfully used in this procedure.

In *ectopic pregnancy*, a fertilized egg is implanted outside the uterus. The egg settles in the *fallopian tubes*, ovary, or abdomen. None of these areas is suitable for fetal development. As the fetus grows, it can burst the organ that contains it and cause severe bleeding, endangering the mother's life. CO_2, YAG, argon, and diode lasers are used to provide *haemostasis* (stoppage of bleeding) by cutting along the length of the tube. After incision of the tube, the products of conception are removed and the incision left to heal by itself. The laser has the advantage that it enables precise incision and haemostasis to occur at the same time. Fiber optic delivery of the beam is used (except for CO_2) because of the ease of reaching the target. In the cases of *isthmo-cornual* blocks as well as reversal of sterilization, CO_2-assisted laparoscopy is employed. The success of laparoscopic techniques using CO_2 lasers is comparable to that of microsurgical techniques.

LASERS IN DENTISTRY

Introduction

Although the potential for lasers to be used in drilling teeth exists, no laser currently available can replace the dental drill. However, lasers *are* used in the treatment of soft and hard tissues and in the welding of dental bridges and dentures. A number of lasers are used in dental procedures; their applications are given in Table 4.

Table 4. Lasers Used in Dentistry

Laser	Wavelength (nm)	Delivery system	Applications
Argon	488 nm, 514.5 nm	Optical fiber	Soft and hard tissues Composite Photo polymerization Endodontrics
Nd:YAG	1064	Optical fiber	Soft and hard tissues Endodontrics
HO.YAG	2120	Optical fiber	Soft and hard tissues
Er.YAG	2940	Articulated arm Hollow waveguide	Soft and hard tissues
CO_2	10600	Articulated arm Hollow waveguide	Soft tissue

Structure of Human Teeth

The basic structure of the human tooth is shown on Figure 30. The part that is visible above the gum is called the *crown*. The unseen part that anchors the tooth is called the *root*. Some teeth have only one root (*incisors* and *canine teeth*), but others have four roots each (*molars* and *premolars*). The middle portion, the gum, is called the *gingiva*. The crown of the tooth is covered by *enamel,* the hardest substance in the human body.

Enamel is composed of 95 percent hydroxyapatite crystals, 4 percent water, and 1 percent organic matter. It is not considered a living tissue. The inner layer of the tooth is called *dentine*. It is less hard than the enamel and is elastic and compressible. It contains tiny tubules that connect to the central nerve of the tooth, which is located in the next inner layer, the pulp. Below the gum, the dentine is covered with a thin layer of *cementum*. It is a hard, bone-like substance to which the *periodontal membrane* is attached. The membrane bonds the root of the tooth to the jaw bone. The pulp is made of soft tissue and contains blood vessels that supply nutrients to the tooth and nerves, which act as thermal sensors. It also contains small *lymph vessels* that carry white blood cells to the tooth and fight bacteria. The extension of the pulp into the root is called the *root canal*. The root canal is open at the end and connects to the surrounding tissue. The tooth's nerves and blood enter the pulp through this opening.

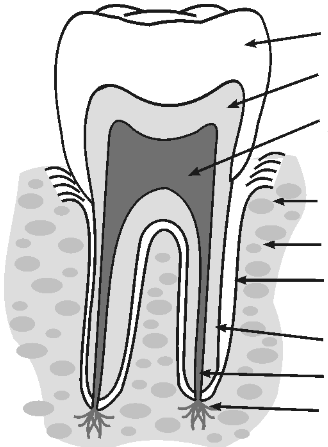

Figure 30 *Structure of human tooth*

Tooth Decay

Tooth decay (*caries*) can be caused by malnourishment and lack of proper oral hygiene. Foods containing carbohydrates such as starches and sugars are major causes of tooth decay. Microorganisms will develop and multiply at the tooth surface to form *plaque*. The plaque interacts with food deposits on the teeth. When enough calcium dissolves from the tooth, the surface of the tooth breaks down and forms a hole called a *cavity* (Figure 31). This decay can develop over several years. The microorganism can also infect the pulp and its interior, inducing severe pain. In such cases, the infected substance must be removed and the cavity filled by suitable alloys such as ceramics or composites.

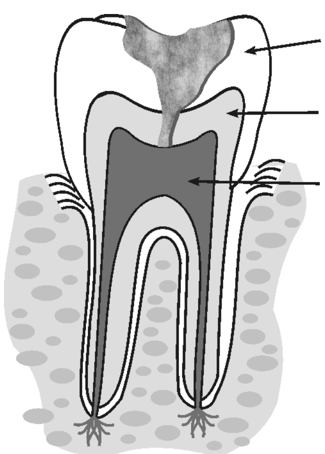

Figure 31 *Schematic diagram showing tooth decay*

The removal of infected substances from teeth is mostly done with a vibrating drill, which usually causes pain. Tooth nerves are sensitive to the vibration and increases in temperature caused by the drill. Lasers have the potential to provide noncontact cleaning. However, at present, because of the heat they generate, lasers cannot replace drills. Both continuous-wave and pulsed lasers induce very high temperatures even with cooling aids. The future lies in the use of ultrashort pulsed lasers. Pico second and femto second pulses may be useful in this area.

Frequency-doubled Nd:YLF lasers with a 532 nm wavelength, a pulse duration of 30 ps, and energy of 500 μJ are successfully used in providing "protection" for the tooth. This is done by sealing the surface of the tooth, thereby significantly delaying the occurrence of decay. This process is effective because the *caries* contain far less calcium than a healthy tooth. Treatment using laser pulses prevents the demineralization process.

Laser Treatment of Soft Dental Tissue

Lesions on the soft dental tissues inside the mouth are common. Some can be malignant, some benign. Removal usually requires surgery. CO_2 lasers can be used to remove these lesions by vaporization. Since the lesions are moist and contain water, the absorption of 10.6 μm laser radiation is very high. Because of this high absorptivity, a 5 to 10 watt pulsed or continuous-wave laser will vaporize the lesion. Because this treatment does not involve physical contact, it is sterile. Moreover, the laser focuses only on a small area and therefore interacts very little with the surrounding tissue. Since small vessels in the lesion are coagulated, no bleeding occurs and no suturing is needed. A defocused beam can be used to smooth the wound's edges.

Of particular importance in laser treatment of lesions is their application to *leukoplakia,* white patches on the mouth membranes. This condition usually occurs in older males with tobacco or alcohol addiction. CO_2 lasers with 10–12 watts of power are used in these cases. Tests have found recurrences to be rare. This procedure can also be performed on the lips and tongue.

Higher-power (20–30 watts) CO_2 lasers are used for treating malignant lesions. Experience has shown that the evaporation caused by the laser is more effective than removal of the lesion with a scalpel. However, this treatment will not prevent the spread of cancer.

Laser Removal of Filling Materials

Sometimes it is necessary to remove older dental fillings, as when tooth decay occurs below the fillings. Er:YAG lasers have been successfully used for this procedure, as well as for removal of dental enamel, dentine, and caries (Figure 32). Using lasers minimizes the damage to the adjacent hard surfaces. Lasers should never be used to remove amalgam. The mercury vapor released can be dangerous to the patient as well as the dentist.

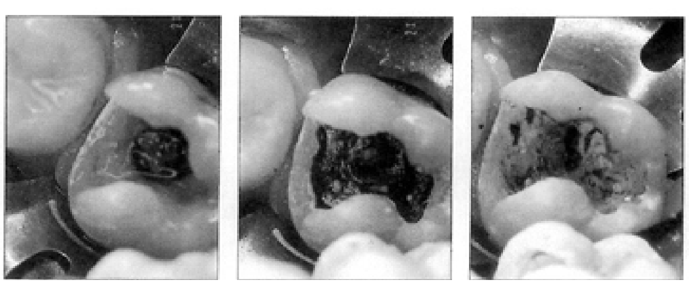

Figure 32 *Use of laser to remove carbonized material from tooth*

CO_2 and Nd:YAG lasers have been used to weld dental bridges and dentures. Lasers eliminate the need for an additional substance for soldering. They fuse the two welded substances by transferring them to a fluid state. It has been demonstrated that laser-welded fixtures have a higher tear threshold than soldered samples. Laser-welded bridges have a higher resistance to corrosion. Lasers also have the advantage of being able to weld different metals and coated alloys.

STUDENT EXERCISES

1. Define the terms *beam divergence, irradiance,* and *coherence*.
2. A CO_2 laser has a power of 300 W and a beam diameter of 1.5 cm. Find the irradiance. If the beam is focused to a diameter of 0.3 mm, what will be its irradiance?
3. Explain the terms *pulse width* and *pulse repetition rate*. If the output pulse of a Q-switched laser has a width of 6 ns and energy of 1.2 J, find the peak power.
4. Explain how a laser beam is transmitted by an optical fiber. What are the causes of loss in intensity?
5. Name some of the most commonly used lasers in medicine. Identify their wavelengths and the applications for which they are best suited.
6. Describe the main parts of the skin. What happens when laser radiation is incident on the skin?
7. The absorption coefficient of a tissue is 4.8 cm^{-1}. If the thickness of the tissue is 0.13 cm, what is the transmission of the tissue?
8. What is the minimum wavelength of absorption for a fair-skinned person? For a dark-skinned person? Distinguish between photo thermal, photo chemical, and ablation effects on tissues.
9. Explain the process of removing diffuse erythema (port wine stains) and tattoos using a laser.
10. What lasers are used in the removal of unwanted hair and facial reconstruction? Explain briefly the techniques used.
11. With the help of a simple diagram, explain the main parts of the eye. What wavelength region of transmission decreases with age?
12. Explain the myopic and hyperopic defects of the eye.
13. Describe briefly the photo thermal and photo coagulation techniques used to treat the retina.
14. Explain briefly the treatment of glaucoma using a laser. How is the tissue welding done using a laser?
15. What procedure is followed in performing a laser-assisted cataract operation? Distinguish between photo chemical and photo disruptive techniques.
16. Using a diagram, explain the major parts of the heart. Which part is the strongest and most muscular? What is its function?
17. What is angioplasty? Describe how laser angioplasty is performed.

18. Explain the term *vascular anastomosis*. How is it performed using a laser?
19. What is TMLR? Describe briefly how TMLR is performed?
20. Explain how laser laparoscopy is performed for endometriosis.
21. Explain how an ectopic pregnancy is treated using a laser.
22. What lasers are used for treating soft and hard dental tissues? What wavelengths are used for each?
23. Using a diagram, explain the major parts of a human tooth.
24. What is leukoplakia? How is it treated with a laser?

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