Lasers in Plastic Surgery

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INTRODUCTION

As is true of any new medical technology, lasers experienced a zealot phase in which applications were far outpacing indications. Indeed, lasers are powerful tools which have revolutionized medicine in the latter half of the 20th century. Plastic surgeons in particular have embraced the use of lasers in their efforts to provide scarless or minimally invasive results. This notion is a bit misguided, as most applications in plastic surgery are based on controlled thermal or ablative injury. We will attempt to review the biophysics and use of lasers to optimize treatment of various conditions while ensuring patient and user safety.

HISTORY

The history of lasers is remarkable and is based on theoretical physics originating from the dissertations of Albert Einstein in 1917.[1] Einstein proposed that light could be induced by stimulated emission of energy in a controlled fashion, and, if harnessed, could have tremendous application. It was known that light, or photonic energy, could be emitted spontaneously from various sources; a random stimulus was all that was required. Einstein's true genius and foresight can be appreciated by noting that it would be four decades before scientists could develop practical applications of his theory.

Ultimately two groups of scientists, Arthur Schawlow and Charles Townes from the United States (Columbia University) and Nikolai Basov and Alexander Prokhovov from Russia (Lebeder Institute in Moscow), independently developed the Microwave Amplification by Stimulated Emission of Radiation (MASER) in 1954.[2] For their work, Townes, Basov, and Prokhovov were awarded the 1964 Nobel Prize in Physics. Schawlow was later recognized with the 1981 Nobel Prize in Physics, which he shared with Nicolas Bloembergan for work in nonlinear optics and spectroscopy.

In 1960, inspired by the work on microwave amplification, Theodore Maiman developed the Light Amplification by Stimulated Emission of Radiation, or LASER system.[3] By using a helical flash lamp surrounding a ruby crystal rod, he generated a new pulsed light source, the first LASER. Prior to Maiman's breakthrough, Gordon Gould in 1957 penned the first document in which the term LASER was used. Gould and his assignee, Patlex Corporation, now hold the basic patents covering optically pumped and discharged excited laser amplifiers. These lasers are used in 80% of the industrial, commercial, and medical applications of lasers. Gould also holds patents on laser uses and fiberoptic communications.

After these groundbreaking ideas and inventions, laser development rapidly progressed. Medical application for laser technology is largely based on the concept of selective photothermolysis described by Rox Anderson and John Parrish in 1983.[4] Table 1 summarizes the exceptional progress that was made possible by cooperation between industry and academia.

BIOPHYSICS

The principle of lasers physics is based on the characteristics of light. Visible light is a form of energy found in the electromagnetic spectrum. It travels as an oscillating wave and behaves by the formula $C=f \times l$ (C=speed of light, f=frequency, l=wavelength).

Speed of light, or velocity, is how fast a wave travels. This is a constant value at 186,300 miles/second (~300,000 kilometers/sec) in a vacuum. The formula tells us that light is a product of its frequency and wavelength. Frequency is the number of wave peaks that pass a given point in space over a fixed period of time; it is expressed in hertz (Hz) or cycles per second. Wavelength is the distance between two successive peaks of a wave measured in nanometers ($nm=10^{-9}m$).

The electromagnetic spectrum (Fig 1) represents all light, a very small portion of which is visible to the human eye. As defined by the above equation,

TABLE 1
Historical Milestones in Laser Development

1960	Sorokin Stevenson	First uranium LASER; second LASER overall	IBM Labs
1961	Javan Bennet Herriot	Helium neon (HeNe) LASER	Bell Labs
1962	Hall	Semi-conductor LASER	General Electric Labs
1964	Geusic Markos Van Uiteit	Nd:YAG LASER	Bell Labs
1964	Patel	CO LASER	Bell Labs
1964	Bridges	Argon ion LASER	Hughes Labs
1965	Pimentel Kasper	Chemical LASER	Univ California, Berkeley
1966	Silfvast Fowles Hopkins	Metal vapour LASER (Zn/Cd)	Univ Utah
1966	Sorokin Lanyard	Dye LASER	IBM Labs
1970	Basov	Excimer LASER (Xenon based)	Lebedev Labs, Moscow
1977	Madey	Free electron LASER	Stanford Univ

frequency and wavelenth are inversely related. At the lower end of the spectrum are longer wavelengths (infrared waves, microwaves, radio waves) with smaller frequencies. The shorter wavelengths (gamma rays, X-rays, UV rays) are found at the upper end of the spectrum and have higher frequencies. Radiation at shorter wavelengths is considered ionizing because of its ability to damage DNA. Exposure to ionizing radiation requires special precautions (ie, lead shielding). Radiation at longer wavelengths is considered nonionizing because it does not damage DNA. Most surgical lasers are of the nonionizing variety.

Visible light falls between 385 and 760nm on the electromagnetic spectrum. There are six main colors in visible light: red, orange, yellow, green,

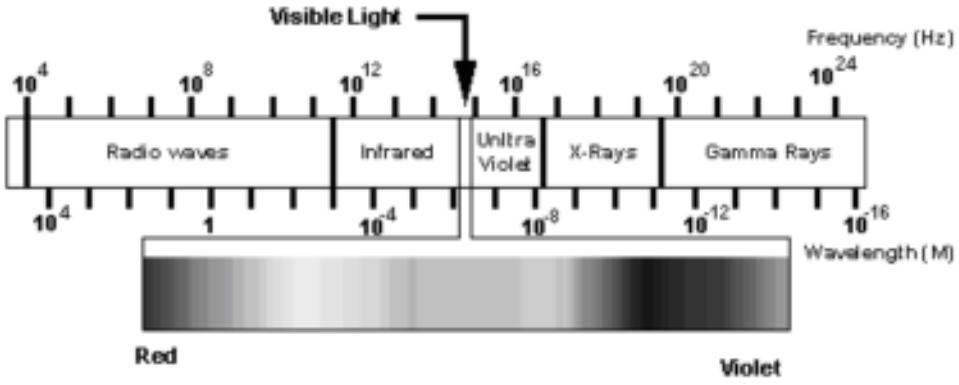


Fig 1. The electromagnetic spectrum including the visible light spectrum.

blue, and violet. Red light has the longest wavelength and the lowest energy, while violet light has the shortest wavelength and the highest energy. Ordinary white light is actually a compilation of electromagnetic waves, all of different wavelengths, travelling in different directions. White light can be separated into component waves (different colors) by a prism.

MECHANICS OF LASERS

At the atomic level, laser light is generated from energy emitted from an atom as it moves from an excited phase to a normal phase. This energy is sometimes released as a photon which has a specific electron energy, or voltage. Electrons orbit an atom in discrete orbital shells. As an atom is exposed to external stimulation from an energy source, these electrons are excited into a higher orbital shell. The atom is unstable at this point and will seek a stable ground state by releasing the surplus energy (photon) as the electrons return to their normal, lower orbital shell. All photons will be similar in character (energy, wavelength) as long as they are generated from the atoms of the same compound or element.

When an atom is struck by a photon emitted from another like atom, it is excited into a higher state before returning to its normal state. This can be a spontaneous occurrence in nature. If an already excited atom is then struck by another photon of equal energy, two identical photons will be released as the atom returns to its ground state in a process referred to as *stimulated emission*. These photons have similar wavelengths and frequencies and exhibit harmonious behavior.

Laser light is different from ordinary light in that it is organized—meaning it is monochromatic, collimated, and coherent (Fig 2).

Monochromatic – all photons in a laser beam exhibit the same color or wavelength because they are from the same source with equal energy.

Collimated – photons travel in parallel fashion, both spatially and temporally, with no significant divergence.

Coherent – photons travel in the same direction and synchronously, or *in phase*.

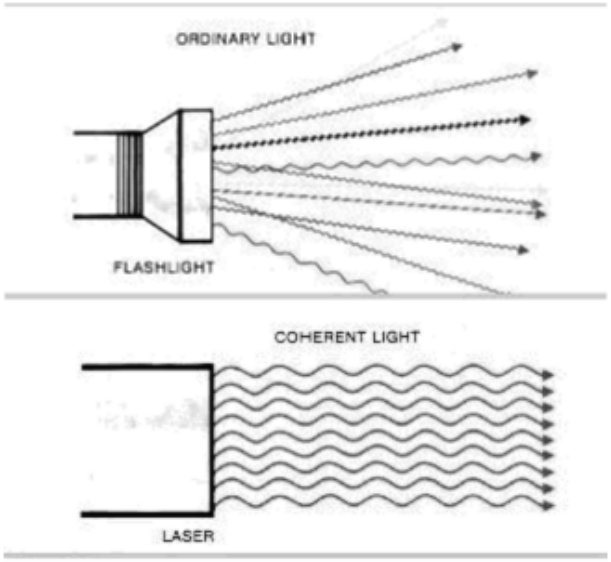


Fig 2. While ordinary light in not organized, laser light is monochromatic, collimated and coherent.

Ordinary light is only in phase for 2 millionths of a meter, while laser light is coherent for 2 to 3 meters.

With the exception of electronic or diode lasers, all lasers must have four critical components: an active medium, an energy source, a rear reflective mirror, and a partially reflective mirror/output coupler (Fig 3).

The active medium can be a liquid (rhodamine 6G dye), a gas (CO_2, argon, krypton, helium–neon, excimer) or a solid state material (Nd:YAG, ruby, alexandrite). The active medium is stimulated by an excitation or energy source such as a light source (eg, flash lamp) or an electrical current. Paired mirrors are located at the ends of this medium: one is the rear reflective mirror (100% reflective) and the other is a partially reflective mirror or output coupler (97%–99% reflective).

A laser beam begins with the stimulation of the active medium by the excitation source. Atoms become excited and release energy as they return to ground state. This energy is transferred as photons to other atoms within the medium; there is no net excess energy during this process. However, when more than 50% of the atoms within a given medium are excited, a population inversion occurs whereby the excess photons generated are colliding with other excited atoms. One photon striking a like-stimulated atom will yield two photons in perfect alignment, with the same energy and wave-

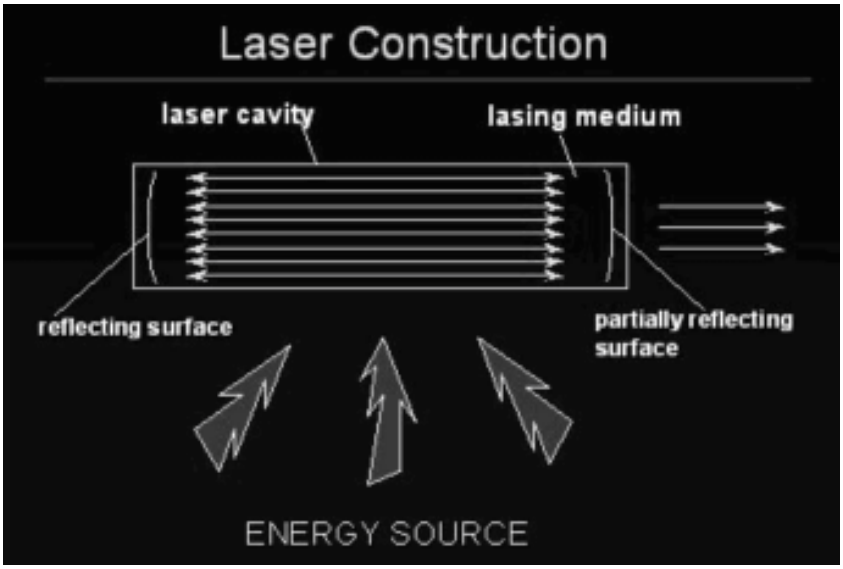


Fig 3. Graphic depicting the four necessary components for laser construction: active (lasing) medium, excitation or energy source, rear reflecting surface, partially reflecting surface or output coupler.

length. Those two will produce four, which will produce eight, sixteen, and so on. This cascade of energy moves back and forth in controlled fashion between the mirrors. When the energy built up exceeds the retaining ability of the output coupler, it is emitted from the medium as a laser beam. This discharge is unique to the composition of the medium.

An important exception to this model is the concept of quality-switching (Q-switch) that was invented by RW Hellworth. Instead of using a partially reflecting mirror, a Q-switched laser uses a rear reflective mirror which is also 100% reflective—not the 97%–99% reflective standard of non-Q-switched lasers. A flashlamp releases light into the laser chamber containing photons until high peak powers have been reached. The Q-switch then dumps the entire contents of the chamber, producing energy in a short, 5–10nsec pulse of very high intensity.

TISSUE EFFECTS OF LASERS

Lasers react with tissues through their thermal, chemical, or photoacoustic effects. Tissues exhibit four responses to light exposure: reflection, absorption, transmission, and scatter (Fig 4). Because any light which is transmitted through or is reflected off a particular substance does not cause local effects, the only clinically relevant effects are absorption and scatter.

In general, absorption is a function of the tissue's affinity for the laser light. A specific wavelength of light is preferentially absorbed by a tissue target

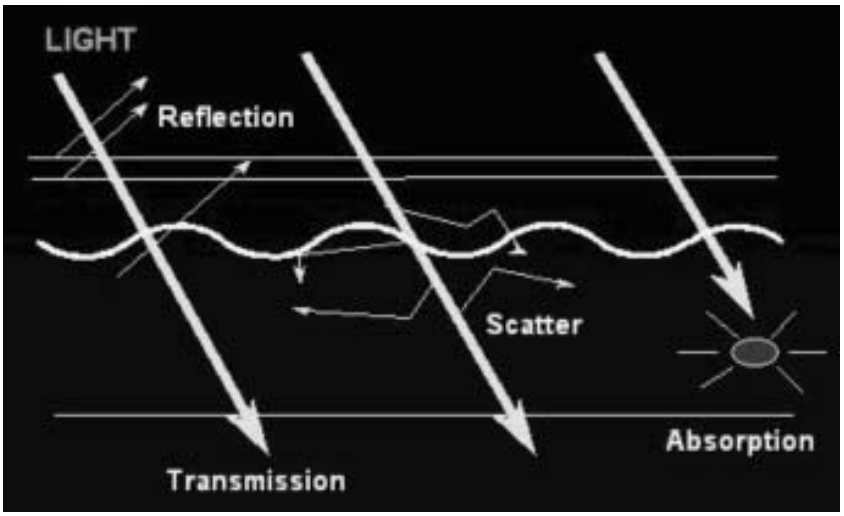


Fig 4. Tissue response to laser light: transmission, reflection, absorption, and scatter.

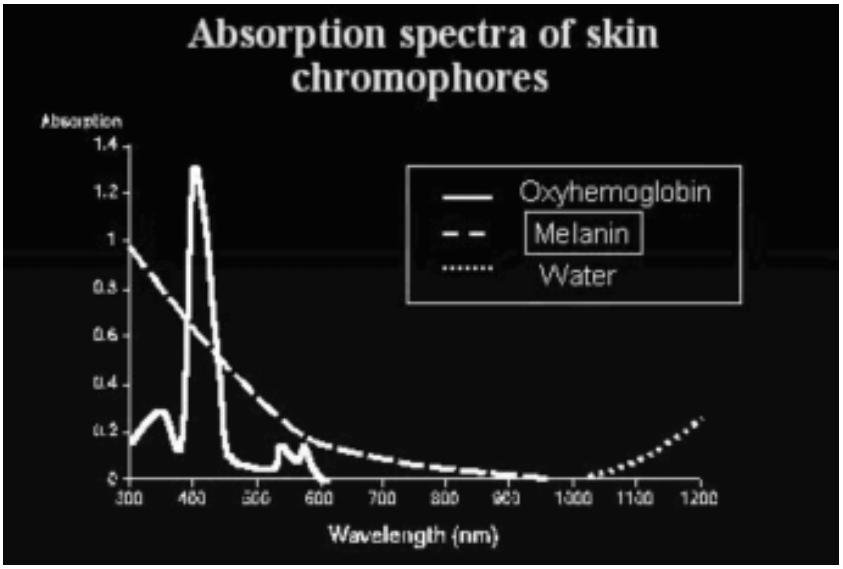


Fig 5. Skin chromophores, oxyhemoglobin, melanin, and water absorb light at specific wavelengths.

chromophore—eg, water, hemoglobin, or melanin (Fig 5). Light scatter is also related to wavelength. Shorter wavelengths demonstrate greater scatter and less tissue penetration. Lasers that give off longer-wavelength light (located on the infrared portion of the electromagnetic spectrum) have deeper tissue penetration (Fig 6).

Lasers that emit light below the visible spectrum (shorter wavelengths) are known as *cold lasers*. Examples of these are excimer lasers ("excited dimer"), often used for angioplasty or photorefractive keratotomy, which induce controlled tissue damage at the atomic level like ionizing radiation. Lasers emitting light in the infrared or visible spectrum exert their effects on tissue by thermal or photoacoustic mechanisms.

Laser functionality is controlled by four variables, as follows: power, wavelength, spot size, and duration of action. *Power* is measured in watts or joules per second. The *wavelength* is measured in nanometers and is specific to the active medium of the laser. Different wavelengths are selectively absorbed by tissue target chromophores. The *spot size* of a laser depends on the focal length of the lens and how the power is distributed over the spot area (transverse electromagnetic mode). It is described in terms of area in cm^2. Spot size affects depth of tissue penetration because larger spot sizes have less scat-

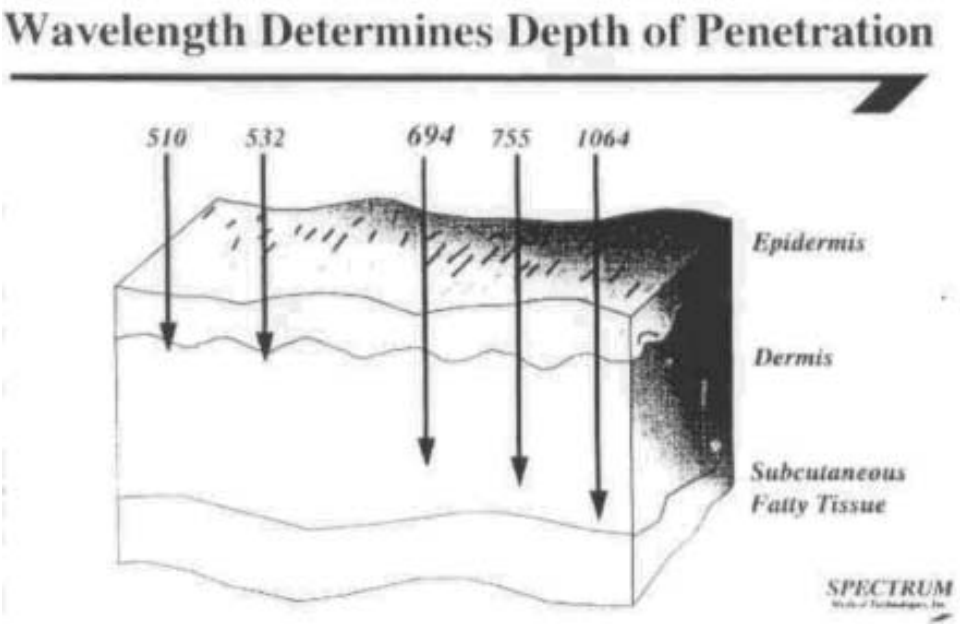


Fig 6. The specific wavelength of light determines the depth of tissue penetration. Laser light emitted in the ultraviolet and visible spectrum (<400 nm to 750 nm) penetrates less deeply than light emitted in the near infrared and infrared ranges (>750nm to 10600 nm).

ter and penetrate deeper (Fig 7). The *duration of action* (pulse width) refers to the total amount of time the tissues are exposed to the laser light.

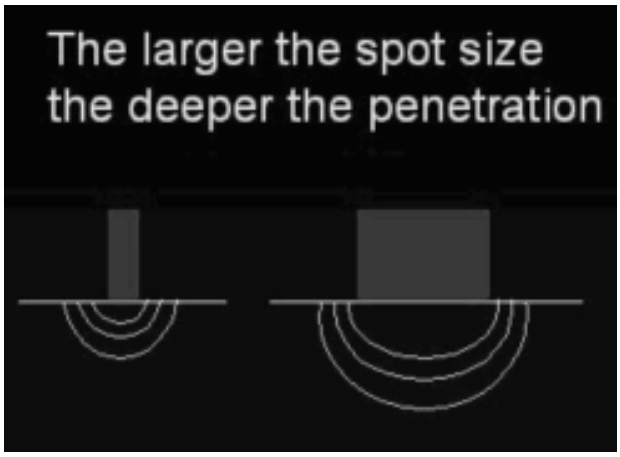


Fig 7. The effect of spot size on tissue penetration.

Power, spot size, and duration of action are all interrelated and can be defined by the following equations:

Power density = power/spot size = W/cm^2
Fluence = power/spot size/time = J/cm^2

Power density represents how many units of energy are delivered to the tissue. Fluence adds the element of time to the equation. Ideally laser application targets a specific tissue while minimizing damage to nontarget tissue (*collateral damag*e). This is accomplished by using the highest appropriate wattage over the shortest possible time.

Chromophores in various tissues have a particular affinity for laser emission of a certain wavelength. They preferentially absorb laser energy over surrounding compounds or substances. Most clinically applicable organic chromophores are water, hemoglobin, and melanin (see Fig 5). Each chromophore has a different absorption spectrum determined by its chemical structure. For example, oxyhemoglobin is the chosen target for lasers designed to treat vascular lesions because it is the predominant form of hemoglobin and has absorption peaks of 418nm, 542nm, and 577nm (Fig 8).

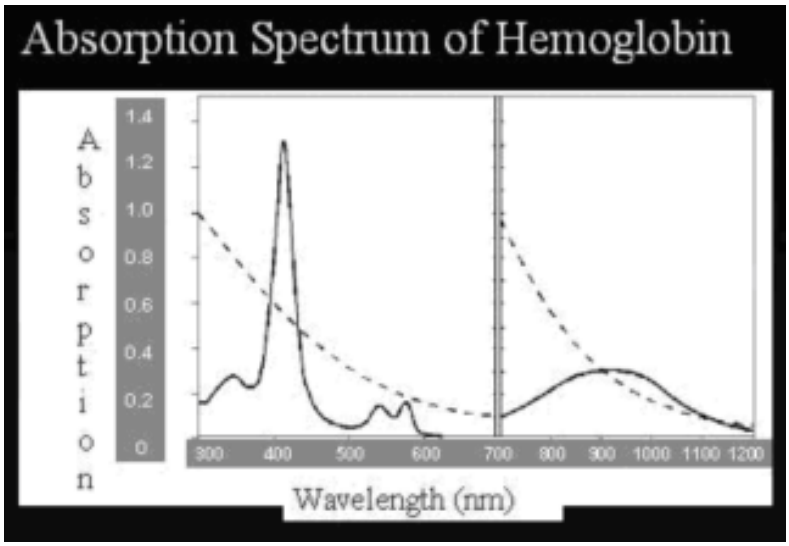
A laser can exert its effect on tissue by thermal, mechanical, or photochemical means (Fig 9).

The *thermal effect* of a laser can occur by three different mechanisms: coagulation, selective photothermolysis, or vaporization. Light absorbed by a target chromophore is converted to heat. The heat generated is determined by the intensity of the light, time of exposure, and the absorption coefficient of the tissue. When the targeted tissue reaches approximately 60°C, *coagulation* occurs.

Selective photothermolysis is the process by which thermal damage is induced in a tissue target that absorbs light at a specific emitted wavelength.[4] The selectivity occurs when the exposure time of the tissue to the laser light is shorter than the cooling time or *thermal relaxation time* (TRT) (Fig 10).

TRT is defined as the time it takes for a specific volume of tissue to dissipate 51% of the energy absorbed. The energy dissipated to surrounding

Fig 8. Graphic representation of the absorption spectrum of hemoglobin with absorption peaks at 418 nm, 542 nm, and 577 nm.



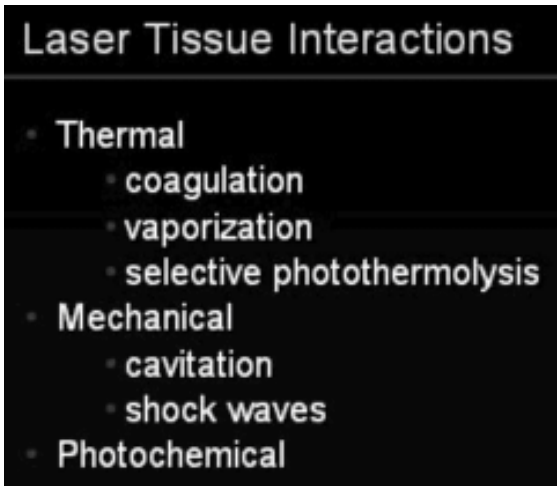


Fig 9. Methods by which a laser exerts its effect on tissue.

Target	Thermal Relaxation Time
200-300 um hair follicle	40-100 msec
100 um PWS blood vessel	5 msec
20-50 um of epidermis	0.2-1 msec
7 um erythrocyte	20 usec
1 um melanosome	1 usec
0.1 um tattoo particle	10 nsec

Figure 10: Thermal relaxation times of common tissue chromophores.

nontarget tissues may cause collateral damage; the longer the relaxation time, the smaller the risk of spread of coagulation necrosis to nontarget structures. Once the TRT has elapsed, another pulse can be delivered to the target without generating thermal damage to surrounding nontarget tissue. Tissue heated to 100°C will *vaporize*.

Lasers used in skin resurfacing are ablative or nonablative. Ablation refers to destruction of the epidermis and upper papillary dermis. With subsequent healing, the collagen in the upper layers of skin is reorganized and remodeled. Nonablative resurfacing spares epidermal destruction and triggers less collagen remodeling with healing.

A laser can also exert a *mechanical effect* on tissue (see Fig 9). For example, selective photothermolysis can target tattoo pigments which act as chromophores for the Q-switched laser light. A photoacoustic *shock wave* is created, fragmenting the pigment into smaller particles that are subsequently cleared from the tissue by macrophages. Collateral damage is slight because the laser light is transmitted in a pulsed mode at high energy.

Although lasers have directed effects on tissues based on absorption by chromophores, their thermal effects are caused by surrounding scatter. The degree of collateral damage or target:scatter ratio can be altered by delivering laser light in either a continuous or pulsed mode. *Continuous* laser light delivered to a tissue results in the diffusion out of the target chromophore and into nontarget surrounding tissue. While very efficient, continuous laser light is technically demanding and usually requires a scanner for safe use. *Pulsed* light intermittently exposes a targeted chromophore to high energy for a very short time, heating up the target in less time than it takes for the heat to dissipate. Collateral tissues are spared from undesired thermal damage, and higher peak temperatures at the targeted chromophores with a lower average power are possible. For these reasons, pulsed lasers are widely used and have distinctive terminology.

Pulse energy is the amount of energy delivered in one pulse. *Pulse width* is the duration of laser application per pulse. The number of pulses delivered over a period of time is expressed in Hertz or pulses/sec.

Recently the concept of skin cooling has gained widespread acceptance.[5-7] *Cooling* is intended to protect the epidermis from thermal damage, and bulk cooling of the entire dermis reduces the risk of third-degree burns. The objective is to maximize target chromophore destruction and minimize damage to the normal overlying epidermis. Cooling allows physicians to use higher doses of energy by increasing the threshold for epidermal damage. Cooling also eliminates heat buildup in the underlying dermis, which in turn minimizes nontarget damage. An added benefit to skin cooling is a reduction in pain and swelling in the treated area.

There are four basic types of skin cooling, as follows:

- bulk precooling – the epidermis and dermis are cooled before light delivery
- dynamic precooling – the epidermis is cooled before light delivery

- parallel cooling – the epidermis is cooled during light delivery
- postcooling – the epidermis and dermis are cooled after light delivery

Common skin cooling devices include cryogen spray;[8,9] cold spray (dynamic cooling);[10] gliding window handpiece; cold handpiece; cold air; and cooling gel.

Lasers differ in principle from electrocautery. Electrocautery uses an electric current to create thermal effects on tissue. This electric current can travel far and irregularly from the applied site. Electricity will follow the path of least resistance and frequently conducts through blood vessels or other fluid channels in the tissue. In contrast, a laser's thermal effects are uniform and local. Lasers have greater tissue specificity, which translates into better clinical efficiency and less collateral damage than seen with electrocautery.

LASER SAFETY

Lasers are medical devices regulated by the U.S. government (*Federal Register* vol 40, pt 2, July 30, 1975). Medical lasers are powerful tools which, if used incorrectly, can result in serious complications for both the operator and the patient.

Lasers are grouped into four classes, as follows.

Class I Lasers – Self-contained (enclosed) systems that do not inflict harm under normal circumstances. These lasers do not require hazard-warning labels because the laser output is at or below the acceptable emission limits. Examples are lasers used for diagnostic work in laboratories.

Class II Lasers – Low-powered devices that emit visible light. Normal protective reflexes such as head turning and blinking are adequate protection when dealing with these lasers. They are safe for momentary viewing, but constant, deliberate viewing without eye protection could cause degenerative eye changes. An example of a Class II device is the helium-neon laser (laser pointer).

Class III Lasers – Require special training for operation. These lasers have the potential to cause injury if viewed directly or if specularly reflected. An examples is the ophthalmologic Nd:YAG laser.

Class IV Lasers – Most medical lasers. These devices are hazardous without proper safety precautions and can cause fires, skin burns, and optical injury from either direct or scattered radiation. Specific safety measures must be observed to prevent injury. Examples include the CO_2, argon, continuous wave Nd:YAG, and pulsed dye laser.

The safe use of lasers in medicine requires user eye protection, patient eye protection, a controlled treatment area, fire safety, smoke evacuation, and accurate documentation.

Eye safety is defined by Maximum Permissible Exposure (MPE) and the Nominal Hazard Zone (NHZ). MPE is the level of laser radiation to which a person may be exposed without hazardous effects or adverse biologic changes in the eye or skin. The MPE is a factor of wavelength, exposure time, and pulse repetition. The NHZ is the space where the level of direct, reflected, or scattered radiation during normal laser operation exceeds the MPE. Beyond this boundary are appropriate exposure levels that are below the MPE.

Ocular injury can occur by various mechanisms.[11] Examples: A CO_2 laser beam (10,600nm) is absorbed by the surface tissues of the globe and results in scleral or corneal damage. Clear plastic shields are sufficient for protection. In contrast, argon (488nm and 515nm) and Nd:YAG (1064nm) lasers emit light that is transmitted through clear fluids. These beams pass through the cornea, are focused by the lens, and strike the retina. The focusing ability of the lens can significantly increase the power density of the laser light and may cause severe injury to the macula. Cataracts and retinal damage can also occur by slow degeneration of the crystalline lens or retinal tissues secondary to chronic exposure to low-power beams.

Eye protection includes the proper use of protective goggles, glasses, or lens covers. They should have the appropriate filtering capabilities to a satisfactory *optical density* (OD). The optical density of the lenses is a mathematical rating system of the lens material's ability to absorb a specific wavelength. A higher OD does not necessarily mean better eye protection. Awake patients can wear goggles or glasses; patients under anesthesia can be fitted with eye pads or corneal shields containing lead.

The laser treatment area must have the following:

- warning signs placed at all entrances
- proper eye protective devices available for all personnel
- window covers
- a secure space for the laser itself

These duties are often the responsibility of a dedicated institutional laser safety officer.

Fire prevention is critical during laser application.[12] Fires can result from either direct laser beam impact or reflected radiation. The laser room staff should be aware of potential hazards and be prepared to react quickly to control a fire—ie, to unplug all electrical equipment and use fire extinguishers. Sterile water or saline should be available to control a small fire. Flammable materials, including skin preparation solutions, should not be used in the immediate vicinity of a laser's target site.

Anesthetic gases containing high concentrations of oxygen—like those within an endotracheal tube or a tube covered by sterile drapes—can ignite and cause fires. Standard endotracheal tubes can be wrapped in wet sponges or reflective foil to prevent combustion, or a flexible metal endotracheal tube can be used. If possible, the oxygen concentration in the inhaled anesthetic should be similar to that of room air.

PVC tubing burns readily and should never be used during laser surgery on the oral cavity or larynx. Nonreflective instruments are recommended to avoid inadvertent laser exposure from scatter or reflection, and the patient's hair may be wetted to minimize fire risk.

The plume of smoke produced during laser application depends on the laser used, duration of exposure, energy delivered, and amount and type of external fluids. Aside from its bad odor and the ocular irritation it elicits, a laser plume is a potential vector for transmission of viruses and bacteria. A number of commercially available smoke evacuators filter particles from 0.1–0.5mcm in size. Surgical masks provide additional protection.

The Joint Commission on Accreditation of Health Care Organizations (JCAHO) decrees there must be meticulous documentation of laser safety measures implemented in all cases. Accurate and complete records help preserve patient and staff safety, provide a legal record in the event of an inquiry or litigation, and serve as an operational log for any future problem-solving or technical support.

In 1985, leaders of the American Society for Laser Medicine and Surgery created guidelines for safe laser use in medical practice (American National Standard for Safe Use of Lasers in Health Care Facilities, 1988; revised 1993, 2002; ANSI Z136.3). A Laser Safety Officer—a physician, nurse, or office professional who has completed training in laser safety—should be appointed to oversee strict adherence to the guidelines and to develop and implement a set of policies and procedures for the facility. For example,

- Composition of the laser committee – laser physicians, nurses, technicians, administrative staff, biomedical engineers, legal or risk management personnel, and a laser safety officer.
- The laser safety officer's job description and duties.
- Guidelines for laser privileges.
- Procedures for medical surveillance.
- Education of personnel.
- Laser therapy procedures.
- Handbook detailing specifics for each treatment area, including
    - control areas for lasers
    - movement of lasers
    - laser eye wear and eye protection
    - detail of documentation
    - storage of laser keys
    - instrumentation in the laser field
    - guidelines for laser endotracheal tubes
    - evacuation of laser plume
    - fire protection
    - anesthesia for laser procedures
    - control of laser foot pedal
    - guidelines for trainee use

The issue of physician supervision of laser procedures continues to be hotly debated, and professional qualification requirements for laser use are currently being considered by legislators. Regardless of whether and when laws are enacted, all persons who use lasers should be intimately familiar with the machine and able to recognize abnormal tissue responses to lessen complications of laser treatment.[13-17]

LASERS (Fig 11)

Several excellent articles review the subjects of cutaneous laser surgery[18-20] and laser principles.[21] Table 2 summarizes common medical lasers and their uses.

Excimer Laser

At 308nm, the excimer laser functions at an extremely short wavelength which limits its tissue penetration. Common medical uses fall outside the field of cutaneous laser surgery and include corrective eye surgery and cardiac angioplasty. However, some benefit in hypopigmented skin[22-24] and psoriasis[25] has been demonstrated.

Argon Laser

The continuous wave and scanner-equipped argon laser functions at 488nm and 514nm wavelengths and produces blue-green light. Oxyhemoglobin and melanin are common target chromophores for this laser. Upon absorption, the laser energy is converted to heat and produces coagulation or vaporization of tissue. Like the Nd:YAG laser, the argon laser's energy is transmitted through clear structures and fluids. The argon laser has been used to treat port wine stains and telangiectasia.

A common problem with the argon laser is the strong absorption by melanin, which leads to scarring and depigmentation. For this reason, argon lasers have been supplanted by the yellow light pulsed-dye lasers. Argon lasers are now more commonly used for ophthalmologic procedures.

Copper Vapor Laser

This laser generates wavelengths of either 510nm (green) or 578nm (yellow). By adjusting the optics, either color can be used. Although its wavelengths are similar to those of the flashlight-pumped pulsed dye laser, the pulses are much shorter: 22nsec vs. 450mcsec for the FPPDL. The thermal relaxation time for the vessels found in vascular malformations is about 0.1–10msec, theoretically ensuring selective vascular coagulation by the 67msec pulse width of the copper vapor laser. Pulses are emitted at extremely high frequencies (5000–15000Hz), so that the copper vapor laser is in effect a continuous-wave device. The thermal effect of one pulse is well within the thermal relaxation time of vascular malformations, but the high repetition rate of pulses results in a much higher net cumulative thermal effect. Clinically this presents a higher risk of hypertrophic scarring than with the FPPDL at similar wavelengths.[26] In some dark vascular lesions with ectatic vessels, the increased perivascular damage and fibrosis may be a desirable effect.

The copper vapor laser uses small spot sizes—100, 150, and 200mcm—that have been effective in treating telangectasias.

KTP Laser

KTP (potassium-titanyl-phosphate) lasers have a wavelength of 532nm and target melanin and he-

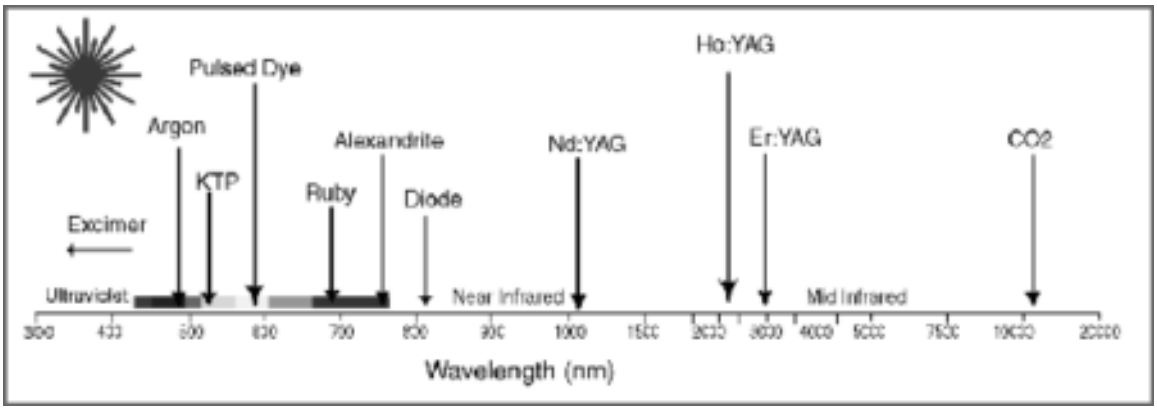


Fig 11. Laser types based on wavelenth and location on the electromagnetic spectrum.

TABLE 2
Characteristics of Common Lasers in Plastic Surgery

Laser	Wavelength (nm)	Target Chromatophore	Common Uses
Excimer	308	Very superficial penetration	Laser eye surgery, cardiac angioplasty, psoriasis
Argon (CW/scanner	488, 514	Melanin, hemoglobin	PWS, telangiectasias
Pulsed dye (green)	510	Melanin, red tattoo ink	Benign epidermal pigmented lesions, red tattoos
Copper vapor (CW)	511, 578	Melanin, hemoglobin	PWS, telangiectasias, lentigines
QS frequency-doubled Nd:YAG	532	Melanin, red tattoo ink	Benign pigmented lesions, red tattoos
KTP (CW)	532	Melanin, hemoglobin	Telangiectasias
Pulsed dye (yellow)	585	Hemoglobin	PWS, hemangiomas, telangiectasias
QS ruby	694	Melanin, dark tattoo pigment	Benign pigmented lesions, dark tattoos
QS alexandrite	755	Melanin, dark tattoo pigment	Benign pigmented lesions, dark tattoos
Diode	800-900	Melanin	Hair removal
QS Nd:YAG	1064	Melanin, dark tattoo pigment	Benign pigmented lesions, dark tattoos
Er:YAG	2940	Water	Rhytides
CO_2 (CW, pulsed)	10600	Water	Rhytides, atrophic scars, various epidermal and dermal lesions
IPL device (by definition, not a laser)	500-1200	Melanin, hemoglobin, tattoo pigment, water	Pigmented lesions, birthmarks, facial spider veins, leg veins, hair removal

moglobin. KTP lasers have been successful in the treatment of small leg veins, melasma, tattoos, port wine stains, and for nonablative dermal remodeling. In melasma the KTP laser gently heats melanosomes with millisecond-long pulses, rather than rapidly destroying the target with Q-switched pulses. This gentle heating can be also be used to treat facial telangiectasias without purpura.

Flashlamp-pumped Pulsed Dye Laser

The flashlamp-pumped pulsed dye laser emits wavelengths of 577nm and targets the oxyhemoglobin in blood vessels for selective photothermolysis of cutaneous vascular lesions. This laser is commonly used to treat hemangiomas,[27-29] and telangiectasia[30,31] and is the first-choice therapy for port wine stains.[32-34]

Penetration into the dermis is up to 1.0mm and epidermis/upper dermis scarring is minimal.[35,36] The energy in the original pulsed dye lasers was delivered with pulse widths approximating 500mcsec and spot sizes of 5–10mm. These pulse widths are below the thermal relaxation time of vessels in port wine stains (up to 1.2msec) and thus result in effective coagulation of targeted blood vessels with minimal surrounding perivascular damage.

At the cellular level, preferential absorption of energy by erythrocytes causes rapid, dose-dependent cell lysis. In addition, vascular endothelial cells are disrupted by heat conduction and me-

chanical trauma within the confines of the vessel walls – a shock-wave effect.

The 577nm FPPDL should be ideal for targeting oxyhemoglobin,[37] yet there is evidence of increased effectiveness with 585nm lasers[10,38] presumably because the slightly longer wavelength penetrates deeper into the tissues to reach more blood vessels and will not be completely absorbed by vessels on the surface.

Selective photothermolysis with the FPPDL typically causes less epidermal injury, fibrosis, and scarring than occur with other lasers. Hyperpigmentation and, even more rarely, hypopigmentation are seldom seen and almost always temporary, usually resolving in 6–8 weeks.[39]

Clinically the FPPDL is ideal for treating the fine pink or salmon-colored port wine stains of infants and children. Darker, purplish colored port wine stains respond less favorably.[40] Port-wine stains contain vessels of various sizes, some of which are resistant to therapy. Increasing pulsewidths have been suggested to treat the larger vessels while thoroughly coagulating the smaller vessels. The usual pulse widths range from 360mcsec to 40msec.

FPPDL therapy is not recommended for treatment of dark-skinned patients. The high melanin content of the skin increases the risk of prolonged or permanent hyperpigmentation and superficial sloughing.

Complete disappearance of a port-wine stain after laser treatment is rare.[41,42] A realistic goal of treatment is 80% fade after 6–8 treatments with FPPDL.

Ruby Laser

The ruby laser was invented by Schawlow and Townes in 1958. It was Goldman in 1963 who first used it on human skin. This laser emits light at wavelengths of 694nm, in the red bands. The Q-switched ruby laser has paired flashlamps which pump energy into a chromium-ruby crystal. The Q-switch device, called a Pockel's cell, opens to allow the photons to reach the rear mirror when enough photons are excited to cause a population inversion. Pulse widths are usually 10–25nsec and are adjusted by how long the Pockel's cell is left open. The pulse repetition is up to 10Hz. This extremely short pulsing or dwell time significantly reduces the thermal effects on the surrounding tissue and creates an additional photoacoustic effect that shakes the tissue violently at the cellular level.

Chromophores for this laser are carbon, blue-black tattoo pigment (common in amateur tattoos), and melanin. It is typically used to remove unwanted hair,[43-45] pigmented lesions including nevus of Ota,[46-49] and tattoos.[50]

Alexandrite Laser

The alexandrite also uses Q-switching and emits light at 755nm in the near infrared bands. Target chromophores include melanin and dark tattoo pigment. This laser is useful for removing dark hair,[51] dark tattoos,[50] and benign pigmented lesions.[52]

Diode Laser

Diodes are essentially one-way valves for electricity that rely on electrical stimulation of solid state semiconductors. Diode lasers are similar in construction to light-emitting diodes. The familiar laser pointers are, in fact, diode lasers. Clinical diode lasers emit near-infrared light in the 800–900nm range. Currently their principal application is in millisecond-range pulsed mode for hair removal[53-57] and in periodontal surgery. Other applications include the treatment of leg and facial veins.[58]

Diode bars can be used to excite or enhance more traditional laser media—eg, YAG rods. Because of their relative simplicity and low maintenance requirements, diode lasers and diode-enhanced solid state lasers will be more frequently used as more wavelengths become available.

Nd:YAG Laser

The Nd:YAG (Neodymium:Yttrium Aluminum Garnet) laser functions in the near infrared range at a wavelength of 1064nm. The active medium is a crystal of yttrium, aluminum, and garnet. It is doped (laced) with a rare-earth element called neodymium that produces the laser light when exposed to flashlamps. The beam is invisible and requires an aiming beam, which is often a 1mW helium-neon pilot laser light. Because of the longer wavelength, depth of penetration can be up to 6mm, producing homogeneous coagulation. The laser is best known for its ability to slowly heat large volume of tissues with deep coagulation and minimal vaporization.

Vessels up to 3mm in diameter can be effectively coagulated with the Nd:YAG laser.

The Q-switched Nd:YAG laser employs a mechanism similar to the Q-switched ruby laser. It is extremely versatile and has multiple clinical applications, including nonablative facial resurfacing,[59] hair removal,[60-62] and for the treatment of hypertrophic scars and acne scars, leg veins,[63-65] pigmented lesions, vascular anomalies,[66] and tattoos.[67,68]

Erbium:YAG Laser

The erbium laser is a solid-state laser that emits light near the infrared portion of the electromagnetic spectrum with a wavelength of 2940nm. Its primary chromophore is water. Typical pulse widths range from 250–350mcsec. The laser can ablate variable amounts of tissue with less thermal damage to surrounding tissues than the CO_2 laser. For example, the zone of thermal necrosis of the erbium laser is usually <50mcm in depth, compared with 75–150mcm for CO_2 lasers. However, by lengthening the pulse width the penetration depth can be extended to ~100mcm to simulate CO_2 laser effects. Variable pulse width erbium lasers can ablate tissue with greater control than CO_2 lasers, which makes them a popular choice for ablative skin resurfacing.[69-74]

CO_2 Laser

Before the advent of the Er:YAG laser, the CO_2 laser was foremost for ablative skin resurfacing. In the 1990s, when pulsewidths were shortened to minimize residual thermal injury, the CO_2 laser became widely popular. In the right hands, exceptional results are possible.

The active laser medium is a combination of carbon dioxide, nitrogen, and helium gases. This mixture of gases is excited by an electrical current to generate a laser beam with a wavelength of 10,600nm, which is in the middle infrared spectrum and therefore invisible. A helium ion light is coaxially transmitted to serve as the aiming beam.

The primary chromophore is water, which comprises 75%-90% of all biologic tissues. At low energies, coagulation of vessels or protein denaturation occurs. At high energies (when tissues reach the boiling point and above), the cellular membranes explode and a smoke plume is generated. The specific amount of thermal build-up determines if cutting, vaporization/ablation, or coagulation occurs.

The depth of penetration can be controlled by altering the power, density, and duration of exposure. At high powers with small beams and short exposures, tissue cutting can be achieved. By enlarging the spot size, the laser beam is effectively defocused and the energy is spread over a larger area, which causes tissue ablation or coagulation.

There are two main types of CO_2 lasers, the free flowing and the sealed tube. The free flowing CO_2 laser uses a gas cylinder containing carbon dioxide, nitrogen, and helium. When the gas is consumed and emptied after laser use, the tank must be replenished before the laser can function again. In contrast, a sealed tube CO_2 laser relies on regeneration of the appropriate mixture of gases. Very little of the CO_2 breaks down, and what is consumed is split into products that catalyze gas regeneration.

The CO_2 laser is a time-tested device and the mainstay of laser incisional surgery and ablative tissue resurfacing.[75-79] New ablative lasers have been developed that utilize both CO_2 and Er:YAG.[80-83]

Intense Pulse Light (IPL) Device

Intense pulse light (IPL) is a flashlamp device, not a laser. IPL devices are based on a noncoherent pulsed light source that emits light from the 500-1200nm portion of the electromagnetic spectrum. Whereas a laser beam delivers only one wavelength of light, pulsed light devices deliver many different wavelengths at a time but, like a laser, may be fitted with filters to eliminate unwanted wavelengths. The emitted wavelengths are tailored to reach specific chromophores and can be modified with each pulse. For example, a 550nm cutoff filter can be used to block light from 500–550nm and allow only wavelengths 551–1200nm to be delivered to the tissues.

Since longer wavelengths penetrate deeper into tissues, they are used to treat deeper targets, while shorter wavelengths are used to treat more superficial targets and lessen damage to deep layers. The surgeon is thus able to vary the light delivered to match the depth of the target and avoid nontarget areas.

Pulsed light can also be delivered in bursts of 1–5 pulses at a time. The duration of each pulse and the delay time between pulses is adjusted to the treatment site. Once again, long bursts are generally better for treating large targets and short, rapid pulses are better for small areas.

Because of the broad range of wavelengths offered by IPL, the devices are versatile and applicable to many situations. Clinical uses of IPL include hair removal,[84] telangiectasia,[85] dyschromia, and nonablative resurfacing.[86,87]

CLINICAL APPLICATIONS IN PLASTIC SURGERY

Skin Resurfacing

The goal of skin resurfacing is to reverse the effects of dermal aging caused by environmental forces (UV damage), dynamic forces (wrinkles from overactive underlying mimetic muscles), and gravitational forces (deep wrinkles from descent of facial fat). Actinic damage manifests as rhytides, skin laxity, dyschromias, and cutaneous malignancies. Skin resurfacing primarily functions to reverse skin damage caused by environmental or actinic damage.

Normal skin has an organized arrangement of elastic fibers on a dense background of well-aligned collagen fibers. The dermis comprises cellular and extracellular components. It derives its structural support from an extracellular matrix made up of collagen. Collagen fibers are triple-helical amino acid compounds that are strengthened by crosslinking of proline and hydroxyproline. There are up to six different types of collagen. In adult skin the most common is Type I collagen, produced by fibroblasts and comprising 80% of the dermal collagen.[88]

Elastic fibers make up a relatively small portion of skin (1%–2 %) and are responsible for the properties of stretch and recoil. They are composed of amorphous elastin proteins and more structured proteins called fibrillin. Glycosaminoglycans, which are polysaccharides linked to proteins in their terminal ends, bind a large amount of water in the dermis and regulate skin hydration. These compounds are important in the regulation of cellular movement, cellular interactions, basement membrane integrity, and collagen and elastic fiber formation.

Other cellular components of the dermis are fibroblasts, mast cells, and macrophages. Fibroblasts are responsible for production of the extracellular matrix (collagen). Mast cells release vasoactive substances which mediate inflammatory responses and promote wound healing. Macrophages are phagocytic cells that remove injured tissue.

Dermal aging is largely the result of solar damage and chronologic aging. Chronologic aging is a result of genetic predisposition, while photoaging is a balance between the damaging effects of ultraviolet radiation and the dermal defense mechanisms (melanin content and antioxidant response). Chronologic aging manifests as decreased number of fibroblasts, mast cells, and blood vessels, with thinning of the dermis. These microscopic changes are seen usually in the eighth decade of life.[89] With aging there is also decreased elasticity as evidenced by fewer elastic fibers.[90,91]

Photoaging is largely responsible for overall dermal aging. The effects of chronic sun exposure can be quite profound. In a process called solar elastosis, normal elastic fibers accumulate in an abnormal arrangement while collagen fibers decrease in number and become disorganized. Sun-damaged skin shows poor organization of collagen fibers with clumps of elastic material interspersed. Layered superficial to this solar elastosis but still deep to the epidermis is a thin zone of dermis called grenz or border zone. The production of this layer is thought to be a reparative process to provide a normal layer of dermis over the damaged dermis and to supply appropriate nutrients to the epidermis.

Skin resurfacing removes the photo-damaged skin to allow dermal regeneration and reepithelialization. A dermal wound is not necessary to stimulate regeneration. Many different methods of skin resurfacing have been reported, including chemical peels and dermabrasion. Chemical peels and dermabrasion can be complicated by variable results and have the potential for excessive dermal damage that leads to prolonged healing or scarring. Chemical skin resurfacing with topical alpha-hydroxy acids increases epidermal thickness by 19%–62% and dermal glycosaminoglycans by 49%–62%.[92] Tretinoin (Retin-A) has similar effects on skin thickness and dermal glycosaminoglycans levels.[93] Skin resurfacing by lasers is a relatively recent technique that holds enormous promise (Fig 12).[94-97]

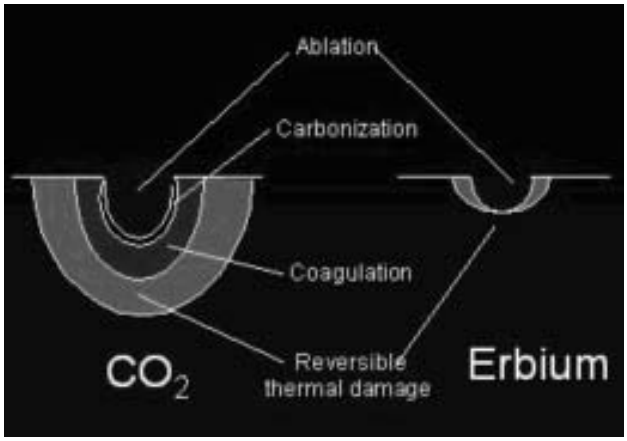


Fig 12. Tissue effects for ablative lasers used in skin resurfacing depicting the deeper tissue penetration and wider zone of coagulation seen with CO_2.

Ablative Procedures

The most common lasers used for skin resurfacing are the CO_2 and the erbium:YAG systems. Early CO_2 continuous-wave lasers have given way to newer short-pulsed and scanned systems with decreased collateral thermal damage.[75,98] CO_2 and erbium lasers are categorized as ablative lasers because they produce epidermal vaporization.

When laser energy is absorbed, a zone of tissue vaporization forms that is surrounded by a zone of thermal injury. The thermally damaged zone is subdivided into areas of irreversible damage (necrosis) and areas of reversible damage. Both zones stimulate an inflammatory reaction which initiates and mediates wound healing. The goal of treatment is to ablate (or vaporize) superficial tissues and to coagulate deeper tissues while averting scarring. A controlled region of thermal injury is desirable, as this is what contributes to collagen remodeling.[99]

CO_2 lasers have a higher ablation threshold than erbium lasers, which results in deeper thermal heating and ablation for the CO_2 laser. The average depth of ablation for CO_2 lasers is 20–60mcm/pass, with an additional 20–150mcm of additional collateral thermal injury. This is true for the first pass, but with each subsequent pass there is less ablation and more thermal injury. The average time for skin to reepithelialize after CO_2 laser treatment is 8.5 days. The erbium laser ablates tissue to a depth of 3–5mcm/pass, with collateral thermal damage of 20–50mcm.[73,100,101] Unlike the CO_2 laser, the erbium laser's parameters hold up with each pass.

The pulse width of variable pulse width erbium lasers can be expanded to 100mcm to increase dwell time on tissue. The erbium laser thus mimics the effect of the CO_2 laser by creating more thermal effect and less ablation per pass. The average time for reepithelialization after treatment with erbium laser is 5.5 days.

The speed of reepithelialization with either laser relates directly to the depth of injury created. Clinically the extent of posttreatment skin erythema correlates with the depth of injury and with the degree of thermal injury. Erythema is more intense and persistent after CO_2 laser treatment—usually lasting for 3–4 months but occasionally present for 6 months or more—than with erbium laser treatment—several weeks.

CO_2 lasers cause skin contraction. Studies have demonstrated 20%–60% long-term reduction in dermal surface area.[102-104] Although the exact mechanism of skin shrinkage is unclear, on histologic examination shortened collagen fibers are seen deep to the zone of thermal damage after laser application. These collagen fibers are thought to be responsible for the apparent skin tightening seen clinically. Other studies suggest that skin contraction is a function of collagen remodeling rather than contraction.[78]

The histologic effects during a pass of an ultrashort-pulsed or scanned CO_2 laser are fairly consistent. The initial pass ablates epidermis and creates epidermis–dermis separation. Any additional passes deliver energy to the dermis, causing an increasing zone of residual thermal damage but with minimal additional true ablation. The region of solar elastosis is thinned after laser application, and the subepidermal grenz zone is thickened in the healing process. The grenz layer contains collagen at a higher density than in normal papillary dermis but less than in scar tissue. On the other hand, the cellular content of this layer is higher than that of scar tissue.[105] The elastic fiber content is reduced during the healing phase. Overall, wound healing is mediated by controlled inflammation, thickening the grenz zone over a thinned layer of solar elastosis. This period of inflammation tends to last longer than the typical acute phase of wound healing, and manifests clinically as prolonged erythema.

The theory that reduced residual or collateral thermal damage allows for faster healing and a shorter inflammatory phase (less erythema) was the impetus for the development of the Er:YAG laser. However, some studies comparing CO_2 and erbium:YAG lasers have shown equivalent healing times when controlling for the depth of ablation and thermal damage.[106,1079] The skin contraction and hemostasis seen with CO_2 lasers is not as readily apparent initially for the Er:YAG lasers, but is almost the same by 90 days.

Both CO_2 and Er:YAG lasers have water as their tissue target chromophore. Peak absorption for water occurs at approximately 2.9mcm, which corresponds to the Er:YAG laser. At 10,600nm, water absorption is still significant, but less than at 2940nm (Fig 13). The increased affinity for water by Er:YAG lasers results in more absorption of energy and more ablation than CO_2 lasers, especially when treating the dermis. The ablation threshold is 1J/cm^2 for erbium lasers vs 5J/cm^2 for CO_2. Ablation with Er:YAG is 3–5mcm/J.

Initially Er:YAG lasers were thought to have only superficial effects, but a deeper ablation level may be achieved with increasing energy. For example, an energy level of 10–20J will ablate 40–80mcm of tissue with each pass. Similar increases in energy with CO_2 lasers extend residual thermal damage, which causes primarily coagulation with minimal additional ablation. Variable pulse width Er:YAG lasers are capable of delivering energy with long pulses relative to the tissues' thermal relaxation time. An increased pulse duration will increase residual thermal damage, so that the erbium laser will behave more like the CO_2 laser. These variable pulse width lasers were developed to have a controllable mix between primary ablation (Er:YAG effect) and primary coagulation (CO_2 effect).

The ablation threshold is the energy required for tissue vaporization. The energy must be delivered within a short enough time to limit surrounding thermal diffusion. The epidermal ablation threshold for CO_2 lasers is approximately 5J/cm^2. CO_2 lasers operate within this ablation threshold to limit

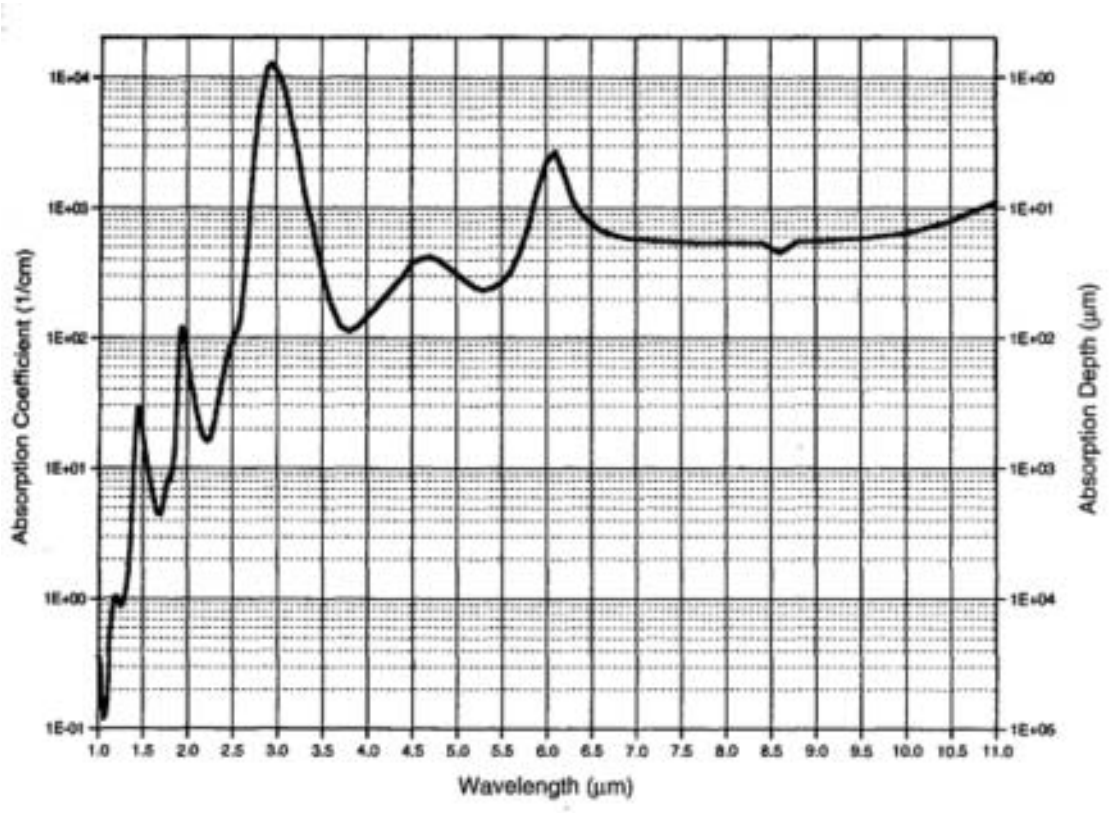


Fig 13. The absorption curve for water demonstrating absorption peaks at 2.9 μm (2900 nm, specific for Er:YAG) and 10.6 μm (10600, specific for CO_2). (*Data from* Hale GM, Querry MR: Optical constants for water in the 200 nm to 200 μm wavelength region. *Applied Optics* 12:555, 1973.)

the surrounding damage on the first pass while *within the epidermis*. On secondary passes nonablative thermal effects predominate, as the ablation threshold for dermis is much higher. With erbium variable pulse width lasers, a deeper penetration in a controlled fashion can be realized by adjusting pulse widths and simply making additional passes. For CO_2 lasers, additional passes in the dermis lead primarily to thermal coagulation, not ablation.

Treatment techniques and parameter settings with both the CO_2 and Er:YAG laser vary widely, although the same basic principles apply. Initial application removes the epithelial layer and causes some dermal heating and collagen shrinkage. Additional passes cause a mix of some degree of ablation with thermal damage and variable degrees of shrinkage. Ablation predominates with erbium, while CO_2 displays more thermal heating/coagulation. The clinical endpoint for CO_2 laser treatment is a pale yellow color of the skin surface, representing treatment depth to the midreticular dermis.[108-110] The erbium laser's endpoints are similar to those of conventional dermabrasion when ablation is the primary mode.[111] When variable pulse width Er:YAG lasers are used, the endpoint becomes less well-defined, and experience is required to optimize outcome and safety.

Comparisons of the CO_2 and Er:YAG lasers in terms of efficacy and postoperative healing have yielded ambiguous results.[107,112-115] It is generally accepted that CO_2 lasers result in longer periods of erythema than Er:YAG devices.[116] Many regard erythema as a sign of collagen deposition,[102,117] while others consider prolonged erythema a treatment complication.[118,119]

Nonablative Procedures (Fig 14)

Because of the increasing desire of patients for minimal downtime and decreased morbidity from elective cosmetic procedures, nonablative laser resurfacing has gained widespread popularity. While the results are highly variable and cannot compare with those obtained from ablative lasers, nonablative techniques are still deservedly popular.[120-122] Nonablative lasers and light sources for skin resurfacing come from both the infrared and visible portions of the electromagnetic spectrum and from broadband light sources.

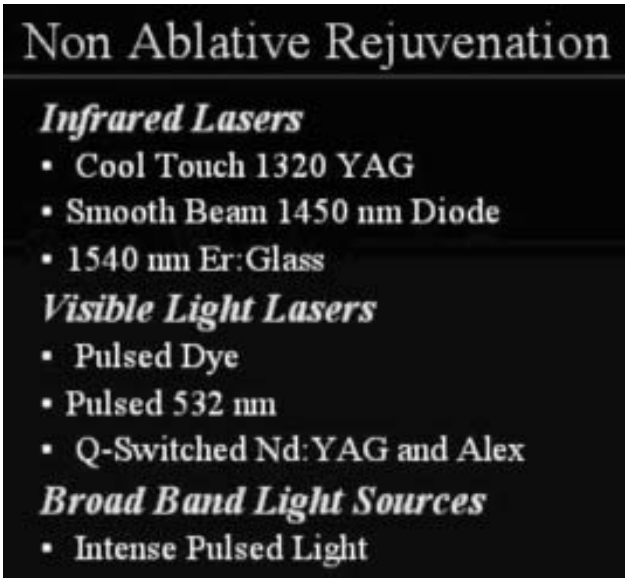


Fig 14. Commonly used lasers and light sources for nonablative skin resurfacing.

Infrared lasers used for nonablative resurfacing include the 1320nm YAG,[123,124] 1450nm diode, and 1540nm Er:Glass.[123,124] Again, while infrared lasers cannot match the results obtained with CO_2 or Er:YAG devices, they have the advantage of a speedy recovery. Candidates for infrared laser treatment must be willing to trade small gains and variability of outcome for the convenience of minimal downtime.

Visible light lasers such as the pulsed dye[127-129] and pulsed 532nm systems and the Q-switched Nd:YAG[87,130] and Q-switched alexandrite lasers conservatively remodel with minimal healing times. With respect to the pulsed-dye laser (585nm), it is theorized that the typical urticaria following treatment represents vasoactively mediated remodeling of the dermal extracellular matrix.

Broadband light sources—Intense Pulse Light systems—have demonstrated impressive versatility and have made an impact on nonablative remodeling.[87] Visible improvements include decreased dyschromia and telangiectasia, reduced pore size, and improved skin texture. Several treatments are recommended to produce maximal effect.

New to the field of nonablative skin treatment are the radiofrequency (RF) devices. Again, these devices are not lasers; in fact, they are thought to act by volumetrically heating tissue independent of photons. Many authors feel RF devices improve

skin texture and tone through dermal tightening and remodeling.

RF devices can be used in monopolar or bipolar fashion. Several companies offer RF technology coupled with nonablative laser systems or an IPL device; these RF systems, however, are radically different in power and effect from the monopolar RF machines.

Most nonablative devices denature dermal collagen while preserving the epidermis. The reorganization of collagen during the healing process reduces clinical rhytides. These systems' wavelengths have lower absorption coefficients than either the CO_2 or Er:YAG laser's, therefore a large volume of tissue can be heated without direct thermal conduction. Most of the energy is absorbed in the superficial layers of the dermis, and surface cooling is required to prevent thermal injury to the epidermis. Scarring and texture change, although rare, are still risks during application.[131]

PATIENT SELECTION BY CLINICAL APPLICATION

Skin Resurfacing

The goals of laser treatment are to optimize delivery of laser energy while minimizing the risk of complications.[16] The indications for laser resurfacing include actinic skin damage, facial rhytides, pigmented lesions, acne and other scars, mild skin redundancy, and dyschromias. Resurfacing will not eliminate vascular conditions such as rosacea and telangiectasia. The choice of laser is based on the patient's expectations and the laser operator's experience and comfort with a given system.

The Fitzpatrick Skin Type classification (Table 3) rates a patient's skin pigmentation and helps to predict pigmentation changes after skin resurfacing.

Patients with skin type I are less likely to have postinflammatory hyperpigmentation after laser resurfacing than those with skin types IV-VI.[77,132] Contrary to popular belief, patients with skin types IV or higher may have less risk of permanent posttreatment hypopigmentation than those with skin types I-III.

Pretreatment skin care regimens help minimize or even prevent adverse pigmentation changes. Usually a 2–6-week course of topical 4% hydroquinone twice a day and 0.05% Retin-A once a day will decrease melanocyte activity, and is recommended for high-risk patients (skin types IV-VI) both pre- and postoperatively. Alpha-hydroxy acids in combination with Retin-A smoothe the skin and even out its texture, improving the outcome of resurfacing.

TABLE 3
Fitzpatrick Skin Type Classification

Type	Color	Reaction to First Sun Exposure
I	White	Always burn/Never tan
II	White	Usually burn/Tan with difficulty
III	White	Sometimes mild burn/Tan average
IV	Medium Brown	Rarely burn/Tan with ease
V	Dark Brown	Rarely burn/Tan with ease
VI	Black	Rarely burn/Tan with ease

Vascular Lesions

Table 4 lists common lasers used in the treatment of vascular anomalies.

Tattoo Removal

Tattoos may be very different in size, composition, and color. Generally, professional tattoos are more difficult to treat because of elaborate mixtures of colors, deeper placement of pigment, and potentially larger size. Amateur tattoos are often smaller, with more superficial placement of pigment. They also tend to be either blue or black, and are therefore easier to treat.

Histologic examination of tattooed skin shows cells containing ink located at the dermis–epidermis junction. Scattered pigments are found throughout the upper dermis and within the cell membranes of fibroblasts. The cells have a surrounding matrix of collagen and elastic fibers. Pigment can also be found outside fibroblast membranes, either free within the cellular stroma or within perivascular macrophages/mast cells.

The stability of pigment aggregates within the fibroblasts depends on the longevity of tattoos. As tattoos mature, the pigments may migrate out of the fibroblasts into deeper dermal levels, into regional lymph nodes, and into perivascular cells.

The pigments used by tattoo artists are quite varied and can elicit intense inflammatory reactions in the skin. Systemic allergic or hypersensitivity reactions are uncommon. Mercury-based (red) pig-

TABLE 4
Lasers Used in the Treatment of Vascular Anomalies.

Laser	Wavelength (nm)	Pulse duration (msec)	Commonly Treated Vascular Lesions
Pulsed dye	585, 595, 600	1.5 - 40	port wine stains superficial hemangiomas
Intense Pulsed Light (IPL)	515 - 1200	1 - 10	telangiectasias, poikiloderma of Civatte
Pulsed 532 nm	532	1 - 50	port wine stains
Pulsed alexandrite	755	3, 5, 10, 20	port wine stains, spider veins
Diode	800	5 - 100	port wine stains, spider veins
Pulsed 1064 nm	1064	50	port wine stains, spider veins superficial hemangiomas

ments can cause allergic eczematous dermatitis, and all pigments can produce foreign body giant cell reactions, granulomas, and sarcoid-like reactions.[133]

Before the advent of lasers, tattoo removal consisted of application of caustic chemicals, salabrasion, cryosurgical ablation, dermabrasion, thermal cautery, and surgical excision. The esthetic results were often mediocre, plagued as they were by incomplete removal, hypertrophic scars, atrophic skin areas or extensive scars, and both hypopigmentation and hyperpigmentation.

Argon laser. The argon laser was the first laser to be used in tattoo removal (Apfelberg et al, 1979).[134] In early series >50% of patients had residual tattoo pigment and 21% had hypertrophic scars. The results of laser treatment of professional tattoos were even worse. Further study showed that while the argon laser's wavelengths of 488nm and 514nm are appropriate for tattoo pigments, their nontarget absorption by hemoglobin and melanin and their limited, superficial penetration caused excessive collateral thermal injury. The poor specificity of the argon laser beam results in diffuse tissue necrosis and subsequent fibrosis. Some of the pigment may slough in the acute posttreatment phase, but the remaining pigment is typically obscured by superficial dermal scarring.[135]

CO_2 Laser. CO_2 lasers have been used to vaporize superficial tissues and tattoo pigments, but their effects deep in the dermis cause thermal injury that invariably produces hypertrophic scars and prolongs wound healing.[136] The mechanism of action of CO_2 lasers is similar to the thermal coagulation of argon lasers—ie, nonspecific destruction of tissue—thus the CO_2 and argon lasers are no longer routinely used in the treatment of decorative tattoos.

Erbium:YAG lasers. At a wavelength of 2940nm, Er:YAG lasers have been used in pulsed fashion to treat tattoos. In contrast to the wide thermal coagulation caused by argon and CO_2 lasers, the Er:YAG system produces minimal collateral thermal damage. They are only minimally useful in treating flesh-colored and other light tattoos and tattoos in the superficial dermis, like facial cosmetic tattoos, however. The effect of the laser is nonselective, and therefore Er:YAG lasers should only be used as a last resort after careful informed consent emphasizing the potential for scar and expectation of incomplete fade of the lesion.

Current laser therapy of tattoos is based on the principle of selective photothermolysis and photoacoustic effects. For tattoo removal, the optimal wavelengths are determined by the absorption peaks of the particular ink. For example, black pigment is absorbed well by all wavelengths and is a competing chromophore with melanin. Blue and green ink absorb wavelengths of 625–755nm, red ink absorbs at 575nm or less, and yellow ink absorbs below 520nm.

Q-switched ruby and alexandrite lasers. Q-switching has revolutionized the treatment of tattoos. The technique of Q-switching involves delivery of extremely high levels of laser energy, which allow for pulse durations in the nanosecond range. The Q-switched ruby and Nd:YAG lasers are associated with striking, permanent dissolution of tattoo pigment with little collateral damage to normal tissue.[137,138]

Taylor's 1990 study elucidated the mechanism of pigment removal.[139] The extremely high energy delivered at short pulses (nanoseconds) causes rapid thermal expansion of pigment granules. Photoacoustic fragmentation of the pigment into microscopic particles then occurs, and these particles are removed by redistribution, transepidermal elimination, and phagocytosis. Because of short pulse widths, thermal buildup and collateral damage are minimal and subsequent scarring is rare.[139]

The Q-switched alexandrite laser emits light at a wavelength of 755nm, which is longer than the ruby laser at 694nm but shorter than the Nd:YAG laser at 1064nm. Typical pulsewidths are 90–100nsec. In 1994 Fitzpatrick analyzed the clinical and histologic effects of this laser.[140] He found good results in the treatment of blue-black and green pigments but a poor response with other colors.[140]

Q-switched Nd:YAG laser. The Q-switched Nd:YAG laser with a wavelength of 1064nm was developed to try to avoid melanin absorption and the resultant hypopigmentation common with Q-switched ruby lasers (694nm).[141-143] The longer wavelength increases the depth of penetration at pulsewidths of 6–10nsec.

The Q-switched Nd:YAG laser is as effective as the Q-switched ruby laser in tattoo removal.[141,142] The response of black ink is excellent, but multicolored tattoos present more of a challenge. Decreased melanin absorption at 1064nm leads to fewer postoperative problems than with the ruby or alexandrite lasers and is safer in dark-skinned patients.[144] The Q-switched Nd:YAG laser has become the workhorse laser for tattoo removal.

Fitted with a KTP crystal, which doubles the frequency and halves the wavelength to 532nm, the Nd:YAG laser is useful in treating red, orange, and yellow tattoos.

Complications are uncommon but can occur with repeated treatment, and include hypopigmentation, hyperpigmentation, textural changes, and scarring. Certain pigments containing iron or titanium oxide particles immediately turn black or brown when treated with lasers. Caution should be exercised when treating red, white, flesh tone, and brown tattoos, which often contain these pigments.[145] Proper wound care is critical in minimizing wound complications.

Treatment of Pigmented Lesions

Certain pigmented lesions are amenable to treatment by lasers.[146] Initially lasers were used for excision of congenital nevi (nevus of Ota and Ito, oculodermal melanosis),[46-49] a darkly pigmented macule typically located in the lateral canthus and temple areas of the face which is refractive to conventional surgery and other ablative methods. The advantages of laser therapy over other treatment modalities are clear: greater precision, higher efficacy, and less scarring. The following lesions are all potential indications for treatment by laser:[147]

EPIDERMAL PIGMENTED LESIONS
- Lentigenes
- Ephelides (freckles)
- Nevus pilus
- Seborrheic keratoses
- Pigmented actinic keratoses

DERMAL PIGMENTED LESIONS
- Blue nevi
- Nevus of Ota
- Nevus of Ito
- Dermal and epidermal pigments (eg, traumatic tattoos)
- Postinflammatory hyperpigmentation
- Melasma

Lesions that should *not* be treated with lasers include any malignant lesion and lesions suspected of being malignant.[147] It may be difficult to identify premalignant lesions or lesions harboring malignant cells; if there is any doubt, a biopsy should be done prior to treatment. Citron[147] states that any nodular, asymmetric, ulcerated, variegated, irregular, large (>10mm), enlarging, or changing skin lesion, as well as any suspicious or questionable pigmented lesion, should be given a wide berth.

Laser treatment of pigmented nevi is controversial at best. Some pigmented nevus cells can remain viable but nonpigmented after treatment, causing problems with cancer surveillance. From an esthetic standpoint, laser treatment of pigmented nevi is doomed to fail. Lesions such as acquired and congenital nevi, junctional nevi, compound nevi, and café au lait macules will fade with laser treatment only to repigment almost invariably.

The response to lasers can be quite varied depending on the laser used, its wavelength and pulsewidth, the energy delivered, and the lesion itself (degree of pigmentation). Sometimes a lesion can lighten or even partly disappear, while at other times and low laser energies, the melanocytes can be activated and the lesion may darken. Temporary or prolonged erythema, textural changes, and scarring can occur as a function of fluence. It is prudent to spot test when possible, although test doses are no guarantee of effectiveness or lack of potential morbidity.

The treatment of pigmented lesions is based on selective photothermolysis. At wavelengths >650nm, laser energy absorption by oxyhemoglobin is low, leading to greater selectivity for melanin at longer wavelengths that penetrate deeper.[148] Q-switched lasers—the alexandrite (655nm),[52] ruby (694nm),[46-48] Nd:YAG (532 and 1064nm)[59]—have short pulse widths and are effective in treating pigmented lesions while minimizing collateral damage. Non-Q-switched lasers and filtered flashlamp devices tend to be less effective, with epidermal cooling recommended to enhance safety.

Incisional Surgery

CO_2 lasers provide hemostasis when cutting in areas where blood vessels are small (< 1mm diam).[149,150] Some authors argue that the thermal damage inflicted with a laser scalpel leads to worse scars than comparable wounds made by cold steel blades. While this is a matter of debate, most studies show no long-term difference between modalities in terms of scarring. Disadvantages of the CO_2 laser include a steep learning curve, potential damage to eyes if proper precautions are not taken, higher cost, and a lack of tactile feedback.

Hair Removal (Fig 15)

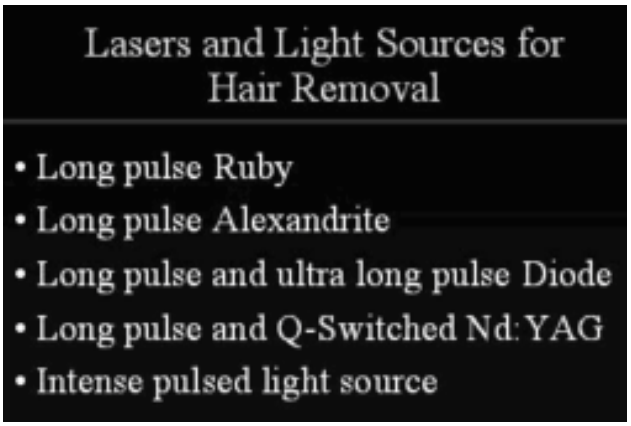


Fig 15. Commonly used lasers and light sources for hair removal.

Hair removal has been traditionally performed with electrolysis, whereby hair follicles are individually destroyed by direct thermal injury. It is estimated that only 15%–20% of follicles are permanently removed by electrolysis. In addition, only small areas can be feasibly treated and it leaves minute scars visible as small follicular bumps.

Goldman noted injury to hair follicles with ruby laser application in 1963. The first controlled study of laser hair removal (ruby laser) was conducted by Grossman and colleagues in 1996.[151] The authors found temporary hair removal at all fluences and permanent removal at fluences >30J/cm^2 for 2 years after a single treatment. Today, permanent hair removal is defined by significant and stable loss of hair for a period longer than the complete growth cycle (usually 1 year).

Hair undergoes characteristic cycles of rest (telogen), transition (catagen), and growth (anagen). A growing hair complex has three anatomic divisions: the bulb, the isthmus or bulge, and the infundibulum. Hair growth originates primarily at the bulb or isthmus and the rapidly dividing matrix cells migrate superficially out of the shaft. On average,

the bulge is 1–1.5mm deep to the skin surface. Both the bulb and bulge contain pluripotential cells that can regenerate an entire hair follicle. It is these two anatomic sites that are important targets for permanent hair removal.

Laser treatment involves selective photothermolysis, particularly targeting the melanin within hair bulbs/bulges which is most active during the anagen phase. The difficulty lies in delivering precise thermal energy to the bulb without targeting melanin in the dermis–epidermis junction; melanocytes are also located in this region. Greater selectivity for follicular melanin can be achieved by cooling the epidermis to reduce superficial injury. It was initially felt that introduction into the hair follicle of an exogenous chromophore with better affinity for laser absorption might be of benefit, but it has proved to have no lasting value.[152]

Not all hair follicles are in the anagen phase at a particular location, therefore repeated laser treatments may be required for optimal results. Treatments should be timed to capture the maximum number of hairs in anagen phase, although in real life this is highly variable and impractical. Depending on the location of the body, hairs have different duration of telogen and anagen. Laser hair removal on the head (telogen 6–12 weeks) can be at 1-month intervals; on the trunk and extremities (telogen 12–24 weeks), 2-month intervals are appropriate. Typically 2–6 sessions are required to achieve optimal hair removal.[153] Most clinical laser centers use treatment intervals of 4–6 weeks.

The best response to laser hair removal is seen in patients with type I–III skin (less melanin) and dark hairs (more melanin). Patients with skin type IV and V have a higher incidence of posttreatment pigmentation changes and scarring, particularly when treated with early hair removal lasers such as the alexandrite, ruby, and short pulse diode system. Dark skinned patients should be treated at lower initial fluences and with aggressive epidermal cooling to minimize complications.

Common systems used in hair removal include the Nd:YAG (1064nm), ruby (694nm), short- and long-pulsed alexandrite (755nm), and diode (810nm) lasers and the Intense Pulse Light (IPL) device. The IPL emits noncoherent light in a continuous wavelength spectrum between 51nm and 1200nm. The IPL relies on filtering for greater selectivity of longer wavelengths that are deeper penetrating. Consistent hair removal after 3–6 months of treatment has been documented.[84,154] The normal-mode ruby laser can be effective in hair removal, but should not be used in dark-skinned or tanned individuals because of prohibitive morbidity.[155]

Long- and short-pulse alexandrite lasers emit light at 755nm and are also effective in hair removal.[518] Connolly reported a reduction in hair density of 86%–88% at 12 weeks.[156] Boss et al found no significant clinical difference between the long-pulse and the short-pulse alexandrite lasers for hair removal, only the short-pulse laser was 5X faster.[157]

The length of the pulsewidth is important in minimizing morbidity and maximizing efficacy. Shorter wavelengths are more effective, but can be used only in light skin types. In dark skin types, longer wavelengths are recommended to limit epidermal damage. The longer wavelength allows epidermal cooling by distributing the heat over a longer time, much longer than the thermal relaxation time for epidermis. One must balance this safety feature of long-wavelength systems against the higher efficacy of short-wavelength lasers.

Diode lasers (810nm) rely on light emission from semiconductor diodes. A sapphire lens is actively cooled to protect the epidermis while transmitting high energy to hair follicles. A common diode laser based on gallium arsenate emits light at 800nm (red-infrared range). This laser allows for longer wavelength, long pulse durations up to 100msec—soon to be 400ms—higher fluences, and direct cooling of the epidermis.
The efficacy of this laser for hair removal is well documented.[53,54,57]

Currently type IV–VI skin types can be very effectively and safely treated with the long pulse diode and Nd:YAG lasers fitted with a cooling device. Specifically, the long pulse Nd:YAG laser has proved to be an efficacious and reliable laser for permanent hair removal. Increased fluence (60–80J/cm^2) and longer pulse duration (50msec) settings are associated with reduced hair counts and improved clinical outcome.[60-62]

Pretreatment sunblock, tretinoin, and/or hydroquinone application can reduce the impact of melanocyte activation. Patients are instructed not to undergo any chemical or mechanical depilation for several weeks before treatment. Hair is then shaved, topical anesthetic (eg, EMLA cream) ap-

plied, and laser treatment performed with or without appropriate epidermal cooling.

Immediately after laser treatment there is parafollicular edema and generalized tissue hyperemia or erythema that lasts 3–5 minutes. The intensity of the reaction diminishes with light colored and sparse hairs. Most patients describe a transient sensation similar to sunburn. The erythema may persist for up to 3 days in the face and up to a week on the trunk.

In conclusion, laser hair removal has been a challenge due to competing chromophores and the prohibitive depth of penetration required for effective treatment, 3000–4000mcm. Advances in laser technology and technical modifications that have led to improved efficacy include the following:[1521]

- longer wavelengths for increased penetration (eg, Nd:YAG)
- larger spot sizes for enhanced coverage
- epidermal cooling to minimize superficial thermal injury
- compression of the skin to reduce the intradermal distance the laser beam must travel, inhibit local capillary perfusion, and decrease the possibility of competing chromophores

Scars

While acne scars are prevalent in most patient populations, their treatment poses a difficult challenge, and long-term results have been marginal at best. In the last decade lasers have been used in combination with surgery (punch excision or grafting), dermal fillers, chemical peels, and dermabrasion.[158,159]

Acne scars are described by their appearance: ice-pick, rolling, and boxcar scars. Ice-pick scars are deep seated and narrow. Rolling scars are undulating, wavy, diffuse, and of variable depth. Boxcar scars can be superficial or deep, round or oval, and have sharply demarcated vertical edges. Boxcar scars resemble chickenpox scars and respond best to ablative lasers that minimize the steep scar wall.

Ice-pick and deep boxcar scars are deeper than most lasers can penetrate, therefore laser therapy is not as effective and they require a surgical approach such as punch excision or fat grafting. Shallow boxcar or superficial rolling scars can be effectively treated with ablative lasers like the CO_2[160,1612] or Er:YAG.[162-164]

Ablative laser resurfacing is often used after surgical excision of deep scars or by itself in the treatment of shallow scars of the rolling or superficial boxcar type. Erbium lasers are preferred because of their effective ablation without thermal collateralization.

The literature is inconclusive as to whether lasers can be effectively used to treat hypertrophic scars. Alster has demonstrated impressive results on sternotomy scars using a pulsed dye laser.[165] Others have failed to see a difference between hypertrophic scars treated with the pulsed-dye laser and those treated with silicone gel.[166] For keloid type scarring, neither the ablative CO_2 laser nor the pulsed dye laser is effective.[167]

The excimer laser may induce repigmentation of hypopigmented scars, vitiligo, and leukoderma.[22-24] It is unclear whether this represents a transient or permanent effect. Further studies are also needed to determine the long-term carcinogenic potential of lasers in the ultraviolet spectrum.

CONCLUSION

From their roots in theoretical physics and Albert Einstein, lasers have transformed modern science. The development of medical lasers has revolutionized the practice of cutaneous surgery and is a testament to the cooperation of industry and academia.

In the last decade the field of laser surgery has virtually exploded with new concepts and technology. Extremely useful tools are now at our disposal, and the future is bright for this field. Nevertheless, we should keep in mind that these devices are not magic wands: They are effective tools indeed, but with true effectiveness comes risk. It is incumbent on all clinicians using these devices to thoroughly understand the physics, dangers, applications, and limitations of lasers so that we can continue to advance our understanding in a reasonable manner both clinically and scientifically.

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