LASERS IN DERMATOLOGY & PLASTIC SURGERY

Snapshot: Fitzpatrick discusses various lasers and their ability to remove skin lesions. He also describes challenges that must be overcome to improve the laser's acceptance in dermatological applications.

Richard E. Fitzpatrick, M.D.
Lasers have been used and studied in dermatology almost from the beginning of their existence. The first skin lesion was treated with a laser in 1962 when Dr. Leon Goldman treated a malignant melanoma with pulsed ruby and neodymium lasers prior to its excision to study the laser's effects on the skin cancer. Histologic examination revealed thermal necrosis of the laser treated areas. Goldman was a major driving force behind the development of laser medicine. His Laser Laboratory at Children's Hospital Research Foundation in Cincinnati, Ohio, was established in 1963 and began investigation of treatment of port-wine stains hemangioma birthmarks, and tattoo removal using ruby, Nd:YAG, and argon lasers.

From the mid-1970s to the early 1980s, clinical work with lasers concentrated primarily on matching the laser's wavelength to a targeted tissue chromophore. As a result, argon and CO₂ lasers became the clinical workhorses of the practitioner. Though excellent clinical results were often obtained, results were, in general, unpredictable and the risk of scarring as a consequence of treatment was significant.

In 1983, Anderson and Parrish published their theory of selective photothermolysis which greatly enhanced our understanding of laser tissue interaction and completely changed the scope of lasers in dermatology over the next decade. The basic principles of this theory are that selective heating is achieved by preferential laser light absorption and heat production in the target light absorbing material (chromophore) with the heat being localized to the target by a pulse duration shorter than the time it takes the target to cool down (thermal relaxation time). For most skin chromophores, the thermal relaxation time is related only to the chromophore's size. Other characteristics, such as chemical composition, are irrelevant.

The first laser which used the principles of selective photothermolysis was the flashlamp-pumped, pulsed dye laser by Candela. This laser was specifically designed to target the 50 to 100 µm ectatic blood vessels in childhood port-wine stain birthmarks, using the oxyhemoglobin of blood as the absorption target. The clinical success of this laser spurred the development of other lasers targeted to specific tissue chromophores and has led to an explosion of interest in lasers in dermatology and plastic surgery by patients as well as physicians.

Lasers and laser tissue interaction

Laser light has several unique characteristics that are useful for dermatological applications. The first of these is mono-chromaticity—virtually all of the light energy generated is concentrated within 1 nm of a single wavelength. This property is important for targeting specific chromophores in skin such as oxyhemoglobin, de-oxyhemoglobin, melanin, various tattoo ink pigments, and water.

The second unique feature of lasers is that the light waves are spatially and temporally coherent—that is, they are aligned in both space and time. Coherent light

![Figure 1. Absorption spectra of the major skin pigments at the concentrations for which they typically occur.*](image)

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Laser</th>
<th>Depth at 50% penetration</th>
<th>Skin chromophores</th>
</tr>
</thead>
<tbody>
<tr>
<td>193</td>
<td>Excimer</td>
<td>0.8</td>
<td>Protein</td>
</tr>
<tr>
<td>396</td>
<td>Tripled Nd</td>
<td>80</td>
<td>Melanin, blood</td>
</tr>
<tr>
<td>488</td>
<td>Argon ion</td>
<td>200</td>
<td>Melanin, blood</td>
</tr>
<tr>
<td>514</td>
<td>Argon ion, dye</td>
<td>300</td>
<td>Melanin, blood</td>
</tr>
<tr>
<td>532</td>
<td>Doubled Nd</td>
<td>400</td>
<td>Melanin, blood</td>
</tr>
<tr>
<td>577</td>
<td>Pulsed dye</td>
<td>600</td>
<td>Blood, melanin</td>
</tr>
<tr>
<td>586</td>
<td>Pulsed dye</td>
<td>600</td>
<td>Blood, melanin</td>
</tr>
<tr>
<td>694</td>
<td>Ruby</td>
<td>1,200</td>
<td>Melanin</td>
</tr>
<tr>
<td>760</td>
<td>Alexandrite</td>
<td>1,300</td>
<td>Melanin</td>
</tr>
<tr>
<td>1,060</td>
<td>Nd:YAG</td>
<td>1,600</td>
<td>Melanin, blood</td>
</tr>
<tr>
<td>2,100</td>
<td>Holmium</td>
<td>200</td>
<td>Water</td>
</tr>
<tr>
<td>2,940</td>
<td>Erbium</td>
<td>2</td>
<td>Water</td>
</tr>
<tr>
<td>10,600</td>
<td>CO₂</td>
<td>20</td>
<td>Water</td>
</tr>
</tbody>
</table>

Figure 2. Typical port-wine stain prior to treatment, showing greater than 75% improvement following six treatments with the Candela pulsed dye laser.

Figure 3. Capillary hemangiomas always go through a rapid growth phase and may enlarge tremendously prior to slow involution over a period of 1 to 10 years.*

Figure 4. Early laser treatment of a capillary hemangioma (above) may result in rapid involution and avoidance of the proliferation phase (below).*

Figure 5. Black and blue tattoo pigment (left) may respond to the Q-switched ruby, alexandrite or Nd:YAG lasers, as demonstrated by this tattoo (right), which was treated in part by all three lasers.

waves are parallel (collimated), resulting in a beam that is non-divergent and one that possesses the same energy density (fluence) without regard to changes in distance. These beams may be focused to a very small, extremely high energy spot.

Lasers such as the argon, argon-pumped tunable dye, and krypton lasers emit a continuous beam of light. Rapid pulsed lasers (kilohertz range) such as the copper vapor, copper bromide, and KTP lasers are, for all practical purposes, no different in their tissue reactions from continuous lasers. The power output of these lasers is in the 1-100 W range. Various shuttering mechanisms and scanning devices have been used with minimal success to avoid unwanted thermal damage, though recent development of millisecond shuttering devices appears very promising.

Pulsed lasers represent the most common type of laser in clinical use. The pulse width of these lasers is typically designed to conform to the calculated thermal relaxation time of the targeted chromophore. Pulsed dye lasers operate in the 0.5 to 1.5 msec range with peak powers in the kilowatt range and are targeted to vascular lesions. Q-switching results in pulses in the 5 to 100 nsec range and peak powers in the megawatt and gigawatt range and include ruby, alexandrite, and Nd:YAG lasers targeted toward smaller structures such as melanosomes and tattoo ink particles.

The carbon dioxide laser has been used as a continuous beam laser, a rapidly pulsed laser with peak powers in the hundreds of watts and a more slowly pulsed laser with much higher peak powers (1,000 W) and also has been used in the continuous mode with a scanning device having a tissue dwell time of less than 1 msec.

Two fundamental processes govern all interactions of light with matter: absorption and scattering. Light absorption is required for any clinical effect in tissue. Essentially all laser-mediated clinical effects are thermal in nature. Sometimes the thermal effects cause secondary reactions, Megawatt, nanosecond pulses heat the target at such a rapid rate that it shatters and supersonic shock waves are created in tissue. All thermal-mediated tissue effects are time and temperature dependent. Most human cells can withstand prolonged exposure at 40°C, but die after 20 minutes at 45°C. In some cases, cells can withstand over 100°C but only for \(10^{-3}\) sec.

The absorption coefficient is the probability per unit path length that a photon at a particular wavelength will be absorbed. It is measured in units of 1/distance and designated as \(\mu_a\) or cm\(^{-1}\). The absorption coefficient depends on the concentration of chromophores present. Human skin has a heterogeneity of pigments with different absorption spectra that allows selective photothermolysis to work (see Fig.1 and Table 1, p. 24).

All light returning from skin is scattered light. As light strikes the skin surface, about 5% is reflected due to the sudden change in refractive index between air and skin. Once inside the skin, the remaining 95% of the incident beam may be either absorbed or scattered. In the dermis, strong wavelength-dependent scattering
by collagen fibers occurs. Penetration of the laser light into the dermis is dominated by this scattering which varies inversely with wavelength. The beam radius or exposure spot size also has a significant effect on penetration, as smaller spot sizes result in greater optical scattering. This is particularly true if the beam radius is less than or equal to the penetration depth of that specific wavelength (the distance that it would be expected to diffuse within tissue).

In general, the depth of penetration increases with wavelength. Short wavelengths of 300 to 400 nm are dominated by strong scattering of the beam as well as absorption by epidermal melanin pigment. These wavelengths penetrate less than 0.1 mm. Longer wavelengths of 1,000 to 1,200 nm penetrate as deeply as 2 mm because of lessened scattering and poor absorption by melanin.

To achieve a clinical effect such as vaporization in tissue, a certain amount of energy must be absorbed. This is measured as energy per unit area, or fluence. In general, as the fluence delivered increases so does the clinical effect. For most pulsed lasers operated within the principles of selective photothermolysis, the fluences necessary for the desired clinical effects are surprisingly similar—in the 3 to 10 J/cm² range. For less selective lasers, the therapeutic range is higher—greater than 15 J/cm².

The rate of the energy delivery is the irradiance or power per unit area. The shorter the pulse duration, the higher the irradiance must be to deliver sufficient energy for clinical effectiveness. However, the speed of energy delivery may have a direct clinical consequence. For example, slow heating will coagulate tissue, while fast heating will vaporize tissue, and extremely fast heating may cause explosive shattering of the heated target.

Clinical use of lasers
In general, the clinical use of lasers in dermatology and plastic surgery involves the removal of unwanted tissue or pigmentation in the skin. For a laser to be clinically valuable it must be selective in its effects, that is, removing only the unwanted tissue or pigment, while sparing the surrounding tissue and not causing scarring. If a lesion can be surgically excised or destroyed in a non-specific manner and reasonable clinical results obtained by these procedures, then use of a more expensive instrument such as a laser may not be warranted or desirable. The use of a laser has excelled in the treatment of those lesions for which there was no successful treatment prior to the development of lasers. These lesions can be divided into three broad clinical areas: vascular lesions, benign pigmented lesions, and tissue ablation applications.

Vascular lesions
Vascular birthmarks are most commonly associated with laser use. Port-wine stains, pink to purple patches which occur as birthmarks of various sizes, shapes, and...
purely cosmetic vascular lesions that are commonly treated with lasers are telangiectasias, or dilated capillary lesions commonly found on the cheeks and nose. Sometimes these lesions are isolated and sometimes they are more densely present in interlacing networks. These lesions are generally very responsive to treatment, but the bruising that occurs from treatment is difficult for many patients to tolerate cosmetically as it lasts about 10 days. The need for more than one treatment session in about 25% of patients is sometimes problematic as well. Larger bluish-purple veins on the nose and cheeks are often unresponsive to therapy, as are leg veins. In addition to the pulsed dye laser, continuous and pseudo-continuous lasers are often used to trace out vessels and do not cause bruising. However, they have the disadvantage of a more non-specific thermal effect that has a greater risk of causing a scar. Argon, argon-pumped dye, copper vapor, krypton, copper bromide, and frequency doubled Nd:YAG lasers have been used with and without various scanning devices for these lesions and have had variable success.

The potential for treatment of leg veins, a huge and lucrative market, by lasers remains an elusive goal. The problems posed by these lesions are their larger size and greater depth in the dermis, their direct communication with the high-pressure deep venous system of the leg, and the need to destroy the thicker pluri-potential cellular venous walls. Energy Systems Corp. (ESC) has developed an innovative filtered flashlamp device that has the capability of delivering various pulsewidths (2 to 10 msec) as well as longer wavelengths (up to 1200 nm) in high energy multiple pulses (up to 90 J/cm² over 3 pulses). This device recently received FDA approval and offers promise in this and other vascular arenas.

The pulsed dye lasers have also proven effective in improving scars of all types (normalizing skin texture and color) as well as treatment of warts and psoriasis. These treatments are thought to be accomplished through vascular-mediated effects.

**Benign pigmented lesions**

Though various short-pulsed lasers (the 510 nm pulsed dye laser, and the Q-switched ruby, alexandrite and Nd:YAG lasers) effectively remove a number of superficial benign pigmented lesions of the skin (lentigines, freckles, seborrheic keratoses) that are considered cosmetically objectionable and are often termed “age spots” by the public, their acceptance for this use has not been tremendous. Other treatment modalities (cryosurgery, acid peels, dermabrasion and treatment with various topical medications, such as Retin-A and alpha hydroxy acid creams) have been commonly used without significant risk of side effects. Other superficial lesions that have been unresponsive to conventional...
treatment (cafe-au-lait birthmarks, melasma—"mask of pregnancy," and post-inflammatory hyperpigmentation) have been unpredictably responsive to lasers. The reason for the poor response appears to be biological factors inherent in the cause of the lesions that remain unchanged in spite of successful lesion removal and cause regeneration of the original lesion.

The primary benefit of these lasers has been in removal of a deep pigment birthmark, called a nevus of Ota, that occurs much more commonly in Asian populations and is seen as a dark blue patch on the face and in removal of decorative tattoos. Treatment of nevus of Ota with Q-switched lasers has been particularly successful, though multiple treatments and slow resolution (approximately one to two years) are necessary. Though removal of tattoos has been very successful, the treatment is by no means ideal, as more than one laser is necessary to effect the range of colors found in tattoos. Commonly, 10 to 20 treatment sessions are necessary, at one to three month intervals. Loss of skin pigment in the treated area is a common occurrence as well, and is avoided to a great extent by using longer wavelengths (1064 nm) that are poorly absorbed by epidermal melanin (see Fig. 5, p. 25).

These lasers work by fragmenting the targeted pigment granules and then allowing tissue macrophages to ingest the fragmented particles and to remove them. (see Fig. 6, p. 26). The need for multiple treatments relates to the depth of tattoo ink as well as the shielding of lower layers by more superficial pigment. Candela, Cynosure, Bio-continuum, and Spectrum are the major manufacturers of the lasers currently in use. Areas of investigation include the use of sub-nanosecond pulses, as well as variations in other pulse parameters. Potential areas of investigation involve manipulation of the macrophage system to stimulate more aggressive pigment removal and new delivery systems for the laser beam. The use of a uniquely efficient OPO system and a specialized delivery system are under investigation by Optokel. Approximately 5 to 10% of the U.S. population is thought to have tattoos now and it is estimated that at least 50% would desire tattoo removal.

An innovative use of these pigment-directed lasers has been in hair removal. There is early data regarding the use of a 1 msec pulsed ruby laser for this purpose. Thermolase has been awarded a U.S. use patent for the combination of an exogenous pigment forced down along the hair follicle to act as a target for an Nd:YAG laser in hair removal. This application has received FDA approval.

**Tissue ablation applications**
The CO₂ laser has been the primary laser used for tissue

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ablation and has been plagued by the existence of unwanted thermal damage under the layer of vaporized tissue that has resulted in poor wound healing and scarring. However, the development of the very high pulse energy UltraPulse CO\textsubscript{2} laser by Coherent has removed this obstacle. The basic principle of this laser is avoidance of unwanted thermal damage by single pulse vaporization, delivering up to 500 mJ/pulse in less than 1 msec. This is accomplished with a collimated beam of 3 mm diameter and also may be aided by rapid precise pulse placement using a computer generated pattern of pulses that overlap 10 to 20%.

Sharplan has developed an alternative technology in which a continuous beam focused to 200 µm is scanned in a spiral of up to 6 mm diameter and has a tissue dwell time of less than 1 msec. Other laser manufacturers are entering this field because of the high demand by the public and physicians for use of these lasers in removing wrinkles and sun damaged skin.

In addition to rejuvenative resurfacing applications, medical use of these lasers includes removal of pre-cancerous lesions, superficial cancerous lesions and various benign growths of the skin such as warts, benign tumors, and certain birthmarks. The use of these lasers for these lesions results in a more simple and precise procedure that has less risk of scarring than conventional treatment.

However it is the rejuvenative applications of these lasers that have captured the interest of the parties involved. As the population has aged in general, and especially as a consequence of the "baby boomers" (2% of the population was age 65 or more in 1900 as compared to 20% projected for 2000) the interest in rejuvenative procedures has expanded tremendously.

The precise removal of fine layers of sun damaged facial skin (50 to 100 µm) has allowed safe and precise removal of the most damaged outer layers of the skin, smoothing the surface irregularities of wrinkling, and formation of new collagen to rebuild the outer layers with healthy new tissue. An unanticipated side effect of this procedure has been the tightening of loose skin occurring from heat-induced collagen fibril shrinkage. From ophthalmological work it is known that collagen shrinkage occurs sharply at temperatures of 55° to 60°C, a therapeutic range below that generally considered to be lethal to skin cells. However, maximizing the skin tightening phenomenon may lead to the ability to perform a non-surgical facelift.

The combination of these three processes—tissue vaporization, collagen shrinkage, and new collagen formation—allows precise treatment of superficial to deep wrinkles with an average improvement of 50 to 70% in an single treatment. Wrinkles around the mouth and eyes, notoriously unresponsive to other treatments, have been noted to be especially responsive, though full face treatment is common (see Fig. 7, p. 26).

Problems associated with the procedure relate to difficulty in vaporizing deeply photodamaged tissue, as successive laser passes contact progressively desiccated collagenous material with little water content to target. Concentration of the laser on these areas may result in tissue heating and heat diffusion resulting in poor wound healing. In addition, areas of thin skin which are known to heal poorly (tops of hands, the anterior and lateral neck, and the upper chest) are often photodamaged as well, but considered risky for resurfacing procedures. Other wavelengths with different coefficients for absorption in water are being examined for these applications (Er:YAG and Ho:YAG lasers).

Other cosmetic applications for these high energy pulsed CO\textsubscript{2} lasers include scar revision and an adjunct to hair transplantation (bloodless, surgical vaporization of recipient sites for hair grafts). Refinement of these techniques is in progress now.

Outlook
Most dermatologists and plastic surgeons who are in clinical practice now did not have an opportunity to learn the use of lasers as part of their residency programs. Today many training programs have incorporated laser surgery as a basic component of the residency program. For those doctors desiring to develop expertise in laser surgery there are several alternatives. Formal post-graduate fellowship programs are available in a university or private practice setting for those wanting a more intensive and comprehensive training of six months to one year or longer. However, the average
The physician receives training more informally through a combination of university- and society-sponsored courses, company-sponsored courses, preceptorships with an expert practitioner, and, of course, study of textbooks and medical literature. The expense and complexity of lasers has been a major barrier in their widespread clinical use. Development of diode lasers has been anticipated but has not occurred. Use of lasers for diagnostic purposes has also failed to develop at a pace that was anticipated.

References

Richard E. Fitzpatrick, M.D. is a member of the Dermatology Associates of San Diego County Inc., a medical and surgical group located in California.