Chapter 1

Laser and Light-Tissue Interactions

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Introduction

Albert Einstein first conceptualized the idea of stimulated emission in 1917. At that time, few realized the potential of this concept. It was not till the 1950s that MASER (Microwave Amplification by Stimulated Emission of Radiation) was discovered that the possibility of inducing stimulated emission in the visible light region of the electromagnetic spectrum was investigated. In 1960, Maiman introduced the first functional laser consisting of a flashlamp pump device incorporating a ruby crystal that produced laser light at a wavelength of 694 nm.

Development of other lasers followed quickly: neodymium:yttrium-aluminum-garnet (Nd:YAG, 1961), argon (1962), carbon dioxide (CO2) (1964) and dye laser (1966) were the first few lasers manufactured. In 1983, a fundamental breakthrough in the understanding of laser/light interactions with the skin was published as the “Theory of Selective Photothermolysis.” This allowed the targeting of specific constituents of the skin without damaging the surrounding tissues. Over time, this translated clinically into the development of more sophisticated laser devices for the treatment of a variety of medical conditions.

Laser

LASER is an acronym for Light Amplification by Stimulated Emission of Radiation. Laser systems (Fig. 1.1) comprise basically four essential components. These include:

1. Laser Pumping System

The unit here provides energy to the laser system. Although the energy sources are usually light and electric current, chemical and even nuclear energy may be used. The energy is transferred into the gain medium exciting the atoms. These become unstable and will release their energy in the form of photons, allowing excited higher orbit electrons to move back to their ground state. This process is known as spontaneous emission. Subsequently, “population inversion” is said to have occurred if more than half of the atoms within the gain medium are in an excited state.

2. Optical Cavity

This is considered the heart of the laser machine. It consists of a highly reflective chamber flanked by a fully reflective mirror and a partially reflective mirror encasing the gain medium. Lasers are named after their respective mediums and they may be semiconductors or exist in a gaseous (e.g. carbon dioxide, excimer), solid (e.g. ruby, alexandrite, neodymium: yttrium-aluminum-garnet, erbium:yttrium-aluminum-garnet), or liquid state (e.g. dye). Semiconductors are electronic devices which have the capability of generating high power with little energy.

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The photon emitted is of a specific wavelength and phase and is determined by the specific gain medium. Within the optical cavity, these photons are reflected back and forth between the mirrors and in their course excite other atoms, which emit exponentially more photons of the same wavelength and phase. This cascade effect results in the process of stimulated emission.

While the fully reflective mirror reflects all photons, the partially reflective mirror allows some photons through into the delivery system.

3. Delivery System

The laser emitted from the partially reflective mirror now enters a delivery system, which may consist of fiberoptic cables (e.g. VBeam™, Candela) or a series of reflective mirrors based within the articulated arms (e.g. Medlite™, QS Nd:YAG, Con Bio). The latter may be considered a more robust and sturdier system. Though the fiberoptic delivery system may be light and maneuverable, they have a fundamental limit in the intensity of the light that it can transmit in the fiber. It is unable to deliver high intensity energies as the optical nonlinearities induced within it can prevent laser operation and/or lead to the material destruction of the fiber.

4. Handpiece

The delivery system terminates in the handpiece, which may emit the laser as a collimated beam or focused beam with the aid of lenses.
Unlike standard light sources, laser exhibits three unique characteristics. These are:

1. **Monochromacity**
   
   When an excited and unstable atom releases a photon of energy, electrons will revert back to their stable original orbit. The photons emitted are identical and the light emission contains only one wavelength, which is determined by the laser medium.

2. **Coherence**
   
   Light can be envisaged as a sine wave. In this context, it travels in phase, both spatially and temporally. Each photon moves in step with one another with military precision.

3. **Focused**
   
   Laser light waves run parallel. As such, the diameter of the beam produced is fixed. It is also of high intensity and able to travel distances with negligible loss of intensity. Furthermore, this parallel beam can be focused to very small spot sizes using a suitable lens. This is widely used in carbon dioxide laser systems which employs focused beams for “bloodless” excisions while using the parallel beams for resurfacing purposes.

**Laser Pulse Characteristics**

Lasers may be further classified based on pulse characteristics, i.e. they may be continuous, pulsed or Q-switched.

Continuous wave lasers (Fig. 1.2) are usually seen in carbon dioxide and argon lasers. The laser emitted is without interruption (continuously) and of low power.

This output remains constant, whereas in a pulsed mode (Fig. 1.3), the laser beam is emitted in a train of narrow, higher peak power pulses with predetermined on- and off time cycles even though the laser switch is depressed. The higher peak power is achieved through pulsing the laser over a shorter period of time. With higher peak powers, tissue incision capability is enhanced. At the same time, with a shorter laser activation time, collateral tissue has more time to cool between pulses, translating to reduced probability of thermal damage. If the laser is able to
generate a succession of pulses at a high enough repetition rate to appear continuous, it may be labeled as quasicontinuous.

Modification to the above results in superpulsing which generates an even higher peak power. Examples of pulsed lasers are pulsed dye laser and ultrapulsed CO₂ laser.

Even higher peak energies can be achieved if the pulse duration is shortened (nanosecond range). This technique is utilized in Q-switched lasers. “Q” refers to the quality factor of the laser cavity and represents the rate of discharge of energy. Q-switching refers to an electromagnetic or chemical switch within the laser cavity that allows the release of all the energy in one brief powerful pulse (Fig. 1.4). This is achieved through inclusion of some type of variable attenuator inside the laser’s optical cavity. When the attenuator is functioning, light which leaves the gain medium does not return, and lasing cannot begin. Initially, the laser medium is pumped while the Q-switch is set to prevent feedback of light into the gain medium. This produces a population inversion, but laser operation cannot yet occur since there is no feedback from the cavity. The amount of energy stored in the gain medium increases as the medium is pumped. After a certain time the stored energy will reach a maximum level. At this point, the Q-switch device is quickly changed, allowing feedback and the process of optical amplification by stimulated emission to begin. Because of the large amount of energy already stored in the gain medium, the intensity of light in the laser cavity builds up very quickly; this also causes the energy stored in the medium to be depleted almost as quickly. The net result is a short pulse of light output from the laser, with very high peak intensity.

### Tissue Optics and Lights

Light may be reflected from or may enter the skin when it strikes the air–skin interface. The minority (approximately 4%) of the incident light is reflected. This occurs as a result of the difference between the refractive index of air and skin. This reflectance of light is determined by the refractive indices of the media, the angles that the incident, reflected and refracted rays make to the interface and the plane of polarization. The epidermis is responsible for most of the reflection from the skin.

The remaining light upon entering the skin may be absorbed, scattered or transmitted. Within the skin, absorption is one of the dominant processes over the ultraviolet (UV) and mid-infrared spectra. The relationship of the absorption of light to the properties of the material through which the light is traveling is best described by Beer’s law. It states that the optical absorbance of a chromophore in a homogenous medium varies linearly with the medium path length, the chromophore concentration and absorption affinity. When light is absorbed, it gives up its photon to a target molecule termed a chromophore. The photon will cease to exist and this quantum of energy transferred excites the chromophore. Without light absorption, there can be no effect on the tissue. In the skin, the three main primary chromophores are melanin, water and hemoglobin. Each of these exhibits its particular band of absorption at certain wavelengths (Fig. 1.5). Melanin, which is predominantly found in the epidermis and hair follicles, may also be found in the
dermis. As its main function is to protect against the detrimental effects of sunlight, its absorption spectrum include mainly ultraviolet and visible light. Water, the main component of collagen, absorbs best beyond the near infrared spectra. Hemoglobin, on the other hand, exhibits peak absorption in the UVA, blue (400 nm), green (541 nm) and yellow (577 nm) wavelengths. With this in mind, the properties of light can be manipulated in terms of its wavelength, pulse duration and energy (fluence) such that a particular chromophore is preferentially targeted, absorbing the light energy and is destroyed while other chromophores are left intact.

Scattering, the other dominant process within the skin, occurs when the incident light is forced to deviate from a straight trajectory by one or more localized non-uniformities in the medium through which they pass. In the skin, collagen fibrils causes most of the scattering. Clinically this is an important concept as scattering reduces the available fluence for absorption and as such potentially decreases the desired effect on the targeted chromophore. The effect of scattering proportionately decreases with increasing wavelengths. This, on the other hand, makes it an ideal modality to reach deeper target tissues based within the deeper dermis, e.g. hair follicles or dermal melanin. In practice, due to lower scattering, a longer wavelength, e.g. 1064 nm laser, will not only be able to penetrate to the level of the deep dermis, to the targeted hair or melanin, but there is also limited absorption by other endogenous chromophores at this wavelength.

The residual light, which has not been absorbed or scattered in the tissue, will be transmitted into the subcutaneous tissues. These are mainly beyond the 700 nm spectra.

### Light Tissue Interactions

Various parameters (Table 1.1) e.g. wavelength, fluence, power, spot size, pulse duration and cooling
method affect laser tissue interactions. Depending on these qualities, the reaction of the tissue to light/laser irradiation is as follows:

1. **Photothermolytic Reactions**

Laser/light tissue interactions invariably produce heat which can denature various cells, e.g. melanocytes, keratinocytes or essential structures, e.g. collagen and blood vessels which make up the skin. Each component within the skin has a threshold for heat injury before it denatures. As such, precise placement of the heat generated by laser/light interactions both spatially and sequentially may preferentially cause damage to the target tissue and at the same time preserve surrounding tissues.

Once a laser impacts the skin, it is absorbed by the tissue producing heat. Thermal relaxation time (TRT) is the time required for the targeted heated tissue to lose half its heat. Therefore the key to successful laser treatment is to affect a thermal effect in the target tissue quickly and cause damage to it before the heat is conducted to the surrounding tissue.

In other words, if we carefully select the laser/light wavelength, with an appropriate fluence and a pulse duration equal or less that the TRT of the target, focal selective destruction of the target occurs with little or no destruction to surrounding tissue (Table 1.2). If the conditions are met, the heat generated should reside within the target until it is damaged without heat dissipating to the surrounding tissue. As a result this will only require minimum light/laser deposition and provide selective damage. This forms the basic concept of “selective photothermolysis.”

Chromophores may also be used as subsurface heat sources to denature nearby tissue targets. This is known as the “extended theory of selective photothermolysis.” This is best illustrated in the scenarios involving hair removal and the treatment of telangiectasias. In hair removal, the chromophore is the melanin in the hair shaft while the target structures like the stem cells within the bulge area have little melanin content. If a longer pulse width is utilized, the melanin laden hair shaft is heated up and significant heat diffusion damages the target stem cells. By the same reasoning, in the treatment of telangiectasias, the laser targets hemoglobin, heats it up and heat then diffuses to the blood vessel wall, coagulating it.

2. **Photochemical/Photodynamic Reactions**

The process usually involves the administration of either a topical or systemic photosensitizer that is subsequently activated by a light or laser source to destroy targeted tissues. With an appropriate light

### Table 1.1.
**Common Laser Terminology**

<table>
<thead>
<tr>
<th>Term</th>
<th>What it Means</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chromophore</td>
<td>Substance that absorbs light</td>
<td>NA</td>
</tr>
<tr>
<td>Wavelength</td>
<td>The distance between one peak or crest of a wave of light and the next corresponding peak or crest.</td>
<td>nanometers (nm)</td>
</tr>
<tr>
<td>Pulse Duration/width</td>
<td>The length of time that the laser is exposed to the skin</td>
<td>nanoseconds (ns) and milliseconds (ms)</td>
</tr>
<tr>
<td>Fluence</td>
<td>The amount of energy delivered to a unit square area</td>
<td>J/cm²</td>
</tr>
<tr>
<td>Power</td>
<td>The rate at which energy is delivered</td>
<td>W</td>
</tr>
<tr>
<td>Spot size</td>
<td>The diameter of the laser upon skin impact</td>
<td>millimeters (mm)</td>
</tr>
</tbody>
</table>

### Table 1.2.
**Selective Photothermolysis Targets**

<table>
<thead>
<tr>
<th>Chromophore</th>
<th>TRT</th>
<th>Pulsewidth</th>
<th>Laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tattoo/pigment</td>
<td>ns</td>
<td>ns</td>
<td>Q-switched</td>
</tr>
<tr>
<td>Blood vessel, Telangiectasia</td>
<td>ms</td>
<td>ms</td>
<td>Pulsed dye</td>
</tr>
<tr>
<td>Venele</td>
<td>sec (s)</td>
<td>ms</td>
<td>Long pulsed</td>
</tr>
<tr>
<td>Hair follicle</td>
<td>ms</td>
<td>ms</td>
<td>Long pulsed</td>
</tr>
</tbody>
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source (e.g. laser, noncoherent light or light emitting diodes), the photosensitizer is excited and subsequently transfers its energy to generate reactive oxygen species within the targeted tissues. The reactive oxygen species causes selective tumor destruction. For example, the tumor selectivity of photodynamic therapy in the treatment of superficial non-melanoma skin cancer is based on the application of the agent (5-aminolevulinic acid) to the tumor (Bowen’s disease or superficial basal cell carcinoma) for 3–4 hours, and then irradiated with red light. The photochemical reaction takes place during illumination with selective destruction and necrosis of the tumor cells.

3. Photomechanical Reactions

These are induced mainly by high power, short pulse lasers. The generation of laser-induced stress waves can disrupt tissue, kill cells, decrease cell viability and increase the permeability of the plasma membrane. Additionally, it may cause erythrocyte vaporization and mechanical vessel rupture with hemorrhage.

4. Photostimulatory Reactions

Experimentally, it has been shown that low energy level laser may be beneficial for wound healing. Although the results suggest possible mechanisms by which the wavelength may potentially influence the cellular responses of injured cells, more work has to be done before the concept can be translated into clinical practice.

Tissue Cooling

Tissue cooling is of paramount importance and has been incorporated into many laser systems. During laser treatment of vascular lesions and hair removal, it is inevitable that epidermal melanin may become an undesired target chromophore. Although this may not be an issue in fairer skin individuals, pigmented skin types may suffer pigmentary side effects or blistering with scar formation. The use of tissue cooling minimizes this risk of epidermal heat accumulation and damage.

Techniques employed to cool tissue vary between different laser manufacturers. In essence, cooling methods involve either the convection or conduction of heat through the surface of the skin. To enhance this process, a gradient of cooler temperature is created on the surface of the skin through one or more of the following processes.

1. Cold Air Convection

Ambient room air is cooled down to \(-30^\circ C\) using a closed loop cooling circuit before targeting it at the area of laser treatment. It may also minimize pain during laser treatments.

2. Contact Cooling

The cooling agent may include chilled liquid between transparent plates through which the laser fires through, which abuts the skin. Sapphire is usually used as it is a much better conductor than glass and its thermal conductivity approaches that of metals. Others may incorporate a chilled moving solid, e.g. copper, as means of heat extraction. These are specially chosen for their high thermal conductivity. Cold gel acts via passive contact cooling. For maximal heat transfer to occur, the contact between skin and the cooling agent must be excellent. To achieve this, firm pressure of the device coupled with gel can be applied together.

3. Dynamic Cryogen Cooling

Here, targeted bursts of cryogen impacts on the skin, allowing evaporative cooling to take place
millisecond before the laser pulse. This method is able to achieve cooling of the tissue up to a depth and temperature of 1 mm and −20°C, respectively.

Cooling may also be divided into three arbitrary phases: pre-cooling, parallel cooling and post-cooling which refers to cooling before, during and after laser exposure. In Q-switched systems, as the pulse duration is very short (nanoseconds), it is difficult to sufficiently cool the skin and pre-cooling is appropriate, providing the epidermal protection. Parallel cooling is more suitable for laser systems with longer pulse durations. Post-cooling may further protect the epidermis as well as reduce discomfort, swelling and erythema.

With cooling, we can expect increased comfort as well as reduced risk of heat accumulation, especially during treatments at higher energy fluence. This in turn can translate to a better clinical outcome. It has been said that cooling will also allow the treatment of darker skin types. This may be true if cooling is used judiciously. Excessive cooling, on the other hand, may cause cryogen-induced injury.

Cryogen-induced injury is more commonly reported in pigmented skin. Post-inflammatory hyperpigmentation due to cold air convection techniques has been reported. A split face study involving 21 patients undergoing Q-switched Nd:YAG laser treatments for Hori’s nevus showed that the cooled sides were significantly more likely to become hyperpigmented after laser irradiation as compared with the uncooled sides. Cryogen-induced arcuate shaped hyperpigmentation has also been reported in dynamic cooling devices.

**Conclusion**

A good understanding of laser/light-skin interactions will enable one to choose an appropriate device and to optimize laser parameters so as to achieve the desired clinical end point resulting in more effective and safer laser/light treatments in all skin phototypes.

**References**