Lasers, Lights, and Related Technologies in Cosmetic Dermatology

Alvaro Boechat, Luis Torezan, and Nuno Osório

Abstract

Lasers have been widely used in dermatology for almost 50 years. Selective targeting of the skin chromophores allowed practitioners to treat many skin conditions which were difficult or had no available treatment until introduction of selective photothermolysis in the early 1980s.

The demand for laser surgery has increased substantially in the past few years. Refinements in laser technology have provided patients and dermatologists with more therapeutic choices and improved clinical results. Innovations have allowed the range of conditions and the skin types suitable to treatment, including vascular and pigmented lesions, scars, tattoos, improvement of photoaging, and hair removal. More recently, fractionated laser devices were developed which contributed to higher efficacy and safety especially for higher skin types.

In this chapter, we present the basic concepts of lasers and tissue optics and also the different laser types, which are classified according to their tissue target and tissue interactions, such as vascular, pigment, photoepilation, and resurfacing lasers. Non-laser technologies, such as intense pulsed light, radio frequency, ultrasound, and cryolipolysis, are also discussed.

Keywords

Laser • Radio frequency • Photothermolysis • Intense pulsed light • Tissue interaction • Wavelength • Ultrasound • Light amplification • Fluence • Stimulated emission

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M.C.A. Issa, B. Tamura (eds.), *Daily Routine in Cosmetic Dermatology*, Clinical Approaches and Procedures in Cosmetic Dermatology 1, DOI 10.1007/978-3-319-12589-3_30

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Introduction

Laser and pulsed light are simply sources of natural light. The visible light that we experience in our day to day is only one facet of a much broader physical phenomenon known as "electromagnetic radiation."

As shown in Fig. 1, the electromagnetic spectrum (Siegman 1986) includes several well-known phenomena, such as TV and radio waves, microwave, infrared, and, on the other side of the spectrum, ultraviolet and X-ray. However, our eyes are sensitive to only a very narrow range of the spectrum, which forms the visible light from violet to red. It is important to realize that each visible color or each emission spectrum is associated with a frequency or wavelength.

Thus, the differentiation between blue and green, for example, is related to their frequencies. It is similar to the musical notes; the difference of the note "do" (C) from the note "sol" (G) or "fa" (F) is their frequencies; one is low pitched and the other high pitched. Drawing a parallel with them, we can see that, in the light spectrum, the higher frequencies correspond to blue and violet and, on the other side of the spectrum, the lower frequencies correspond to red. As light frequencies are very high, of the order of millions of hertz, they are characterized by their wavelength, or the distance between two adjacent peaks in the wave illustrated in Fig. 2 (Siegman 1986; Arndt et al. 1997).

Light radiation may be defined as the point-to-point power transmission in space, regardless of the medium in which it is being propagated. Light or electromagnetic radiation propagates at a high speed in the open space independent of the transmission medium in the form of waves that can travel in the vacuum or in spaces containing matter, such as gases, liquids, or solids. As it enters, or moves from, a different medium, it will suffer changes in direction and speed of propagation.

Lasers are sources of electromagnetic radiation, or light, with some special characteristics that are different from other light sources, such as a car headlight or a lamp.

The word **laser** is an acronym for **light amplification by stimulated emission of radiation**. We can divide this acronym into two well-defined parts: the stimulated emission phenomenon and the light amplification.

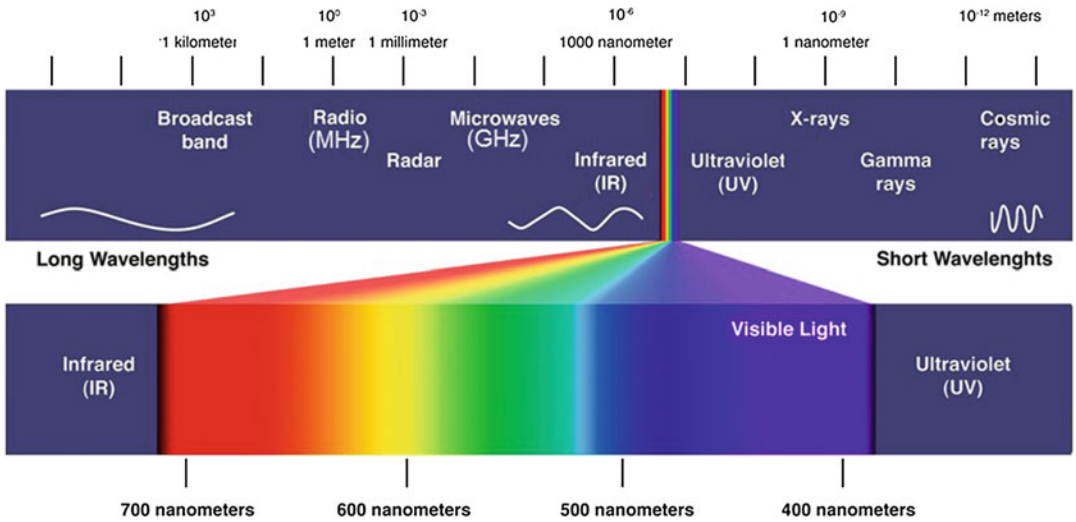

Fig. 1 The electromagnetic spectrum

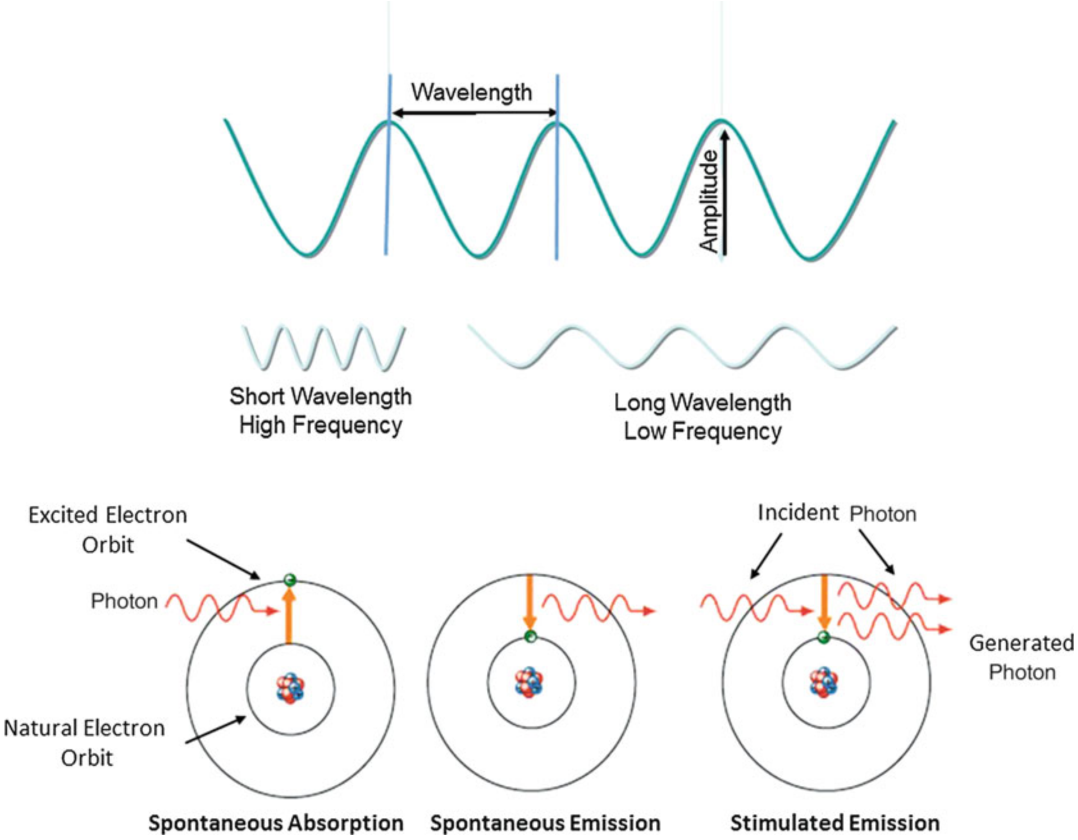

Fig. 2 Electromagnetic waves of photons that transport energy

Stimulated Emission

Light is a form of energy generated, emitted or absorbed by atoms or molecules. To emit energy, the atom or molecule is raised to an excitation energy level, above its natural resting state (in which there is excess energy to be discharged). Atoms cannot maintain the excitement for long periods of time. Consequently, they have a natural tendency to eliminate the excess energy in the form of emission of particles or packets of light waves called photons (Fig. 3a). This phenomenon is called spontaneous emission of light. The wavelength (λ), or the frequency of the emitted photons, is related to the photon energy through the relationship:

$$E_{photon} = hc/\lambda$$

h – Planck universal constant = 6.6260693 × 10^{-34} J.s
c – Speed of light = 300,000 km/s
λ – Wavelength of the light (nanometers – nm)

Each atom or molecule in nature has different energy levels of excitement. Consequently, each element emits photons with different energies and different wavelengths (frequencies). All these primary radiations are monochromatic. The fact that the sunlight is polychromatic indicates that it is composed of a mixture of several distinct elements.

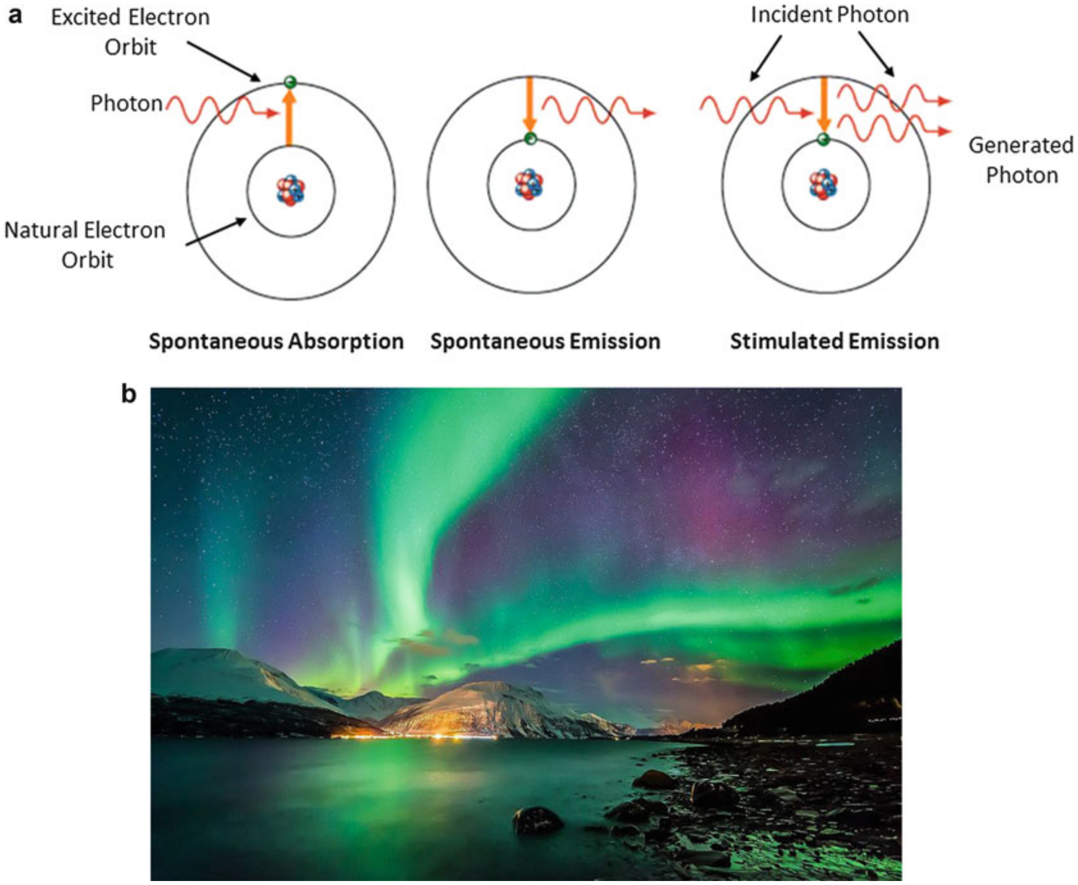

Fig. 3 (**a**) Spontaneous emission of light. (**b**) Northern Lights, or *aurora borealis*, example of spontaneous emission of light

Atoms can be excited by different mechanisms: heat, mechanical shocks with other particles as an electrical discharge (collision with electrons), or when they selectively absorb electromagnetic radiation energy from other photons. This is a natural process that occurs all the time around us, but as its magnitude is very small and very narrow in the visible spectrum, we cannot see it. The location on Earth where we can more easily observe this phenomenon is, for example, near the North Pole, with the famous Northern Lights or auroras. It is produced by the impact between air molecules and cosmic particles from the sun that constantly bombard Earth, producing a phenomenon of luminescence in the upper atmosphere (Fig. 3b).

However, atoms can also decay producing light radiation in a stimulated form. In 1917, Albert Einstein postulated and proved the existence of this mechanism (Siegman 1986; Wright and Fisher 1993; Arndt et al. 1997). When an excited atom collides with a photon, it instantly emits a photon identical to the first (Fig. 3a). This stimulated emission follows the following basic laws:

(a) The stimulated photon travels in the same direction of the incident.
(b) The stimulated photon synchronizes its wave with the incident.

In other words, the waves of the two photons align their peaks adding their magnitudes and thereby increasing the intensity of the light. Photons with aligned peaks produce a coherent (organized) light. In a coherent beam, light travels in the same direction, in the same time, and with the same energy.

The end result of a stimulated emission is then a pair of photons that are coherent and that travel in the same direction. The stimulated emission of light is the working principle of a laser, invented more than 50 years after the discovery of Einstein.

Light Amplification

To illustrate the generation of light inside a laser, let us first imagine a rectangular box or a tube, as a straight cylinder, with a large amount of identical atoms or molecules. As an example, a fluorescent lamp tube with its gas. At each end of the tube, we place mirrors, which because of the construction will be parallel to one another. At one end, the mirror is totally reflective (100% mirror), and at the other end (the exit window of the light – output coupler), the mirror is partially reflective (80% mirror), so that part of the light is reflected back to the tube and part is transmitted through the mirror to the outside (Wright and Fisher 1993; Kulick 1998; Boechat 2009; Raulin and Karsai 2011; Kaminsky Jedwab 2010).

Let us also imagine that the atoms are excited to a higher-energy level by an external source (a light source or an electrical discharge), as if we had activated the switch turning on the lamp. Through the mechanism of spontaneous emission, which takes place completely randomly, the atoms emit photons that begin traveling in various directions within the tube. Those hitting against the tube wall are absorbed and lost as heat, disappearing from the scene. In the case of a lamp, they leave the tube into the environment, illuminating the room. On the other hand, the emitted photons traveling parallel to the tube axis are likely to find other excited atoms and thus stimulate the emission of additional photons, which are consistent with the stimulating photon and travel in the same direction – i.e., along the longitudinal axis of the tube. These two photons continue their journey, again with the likelihood of stimulating, through a similar process, two additional photons – all consistent with each other and traveling in the same axis. The progression continues indefinitely, and 8, 16, 32, 64, etc., photons are produced, all traveling in the same direction, as illustrated in Fig. 4.

It is clearly established a light amplification process that generates a large luminous flux in the longitudinal direction of the tube.

The mirrors perpendicular to the tube axis reflect the photons back intensifying this effect of amplification. Each of these reflected photons traveling along the axis in the opposite direction contributes to the chain reaction effect generating a stream of coherent photons. When they reach the partially reflecting mirror, 80% of the photons return to the tube continuing the amplification

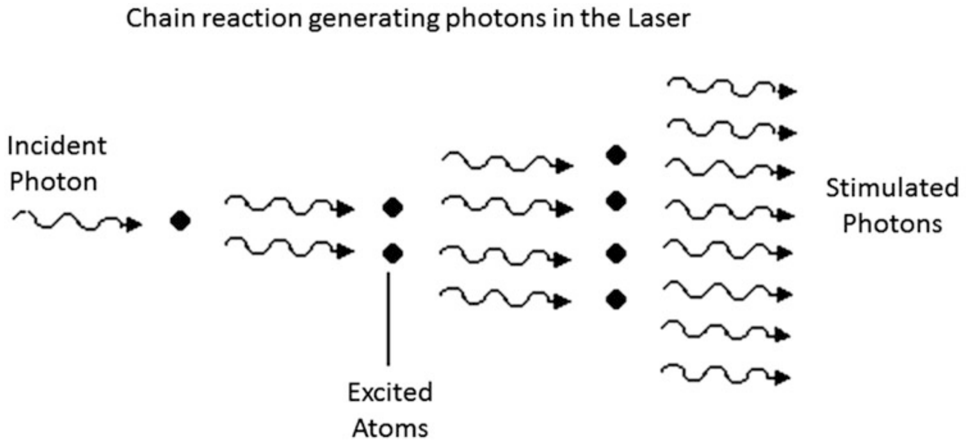

Fig. 4 Chain reaction producing photons inside the laser resonator

effect. The remaining 20% goes out forming the laser beam (Fig. 5a, b). They represent in absolute terms a very intense beam of photons produced by the amplification effect. The tube and its excited medium, together with the mirrors, are called the resonator (or oscillator) which is the basic components of a laser in addition to the excitation source.

Characteristics of a Laser Light

As described above, the laser light has unique properties that make them different from other light sources (Goldman and Fitzpatrick 1994; Arndt et al. 1997; Kaminsky Jedwab 2010; Sardana and Garg 2014):

(a) **Monochrome**: it is generated by a collection of identical atoms or molecules; thus, all photons emitted have the same wavelength, a single frequency. This feature is important because of the selective absorption of the human tissue, which will be presented in the next section.

(b) **Coherent**: because of the stimulated emission and the way the light is amplified, which is only in the longitudinal direction inside the resonator, the photons are organized, as soldiers marching in a military parade. This is called spatial and temporal coherence. At any point of a laser beam, the photons (or light):

 (a) Have the same power
 (b) Travel in the same direction
 (c) Travel at the same time

Being coherent, light from a laser is called collimated. Traveling parallel to the tube axis, the laser beam has a very small divergence angle, i.e., the light does not spread; the photon beam is collimated (parallel). The small divergence allows the use of a lens system to concentrate all the energy of the laser in a precise way on a small focal spot (spot size), achieving a greater concentration of light energy or brightness. Optical laws tell us that the smaller the divergence, the smaller the focal point. When we focus a common light source such as a lamp, of incoherent light, the focal point will be too large and imprecise, whereas when using a laser, we have a very fine and extremely precise focal point and therefore a much more intense effect on the tissue.

Energy, Power, Fluence

The increase of temperature or the effect of treatment on the tissue depends on the amount of energy that it receives. The energy, power, and fluence (energy density) are the physical parameters that control the treatment effect and determine the eventual increase in temperature.

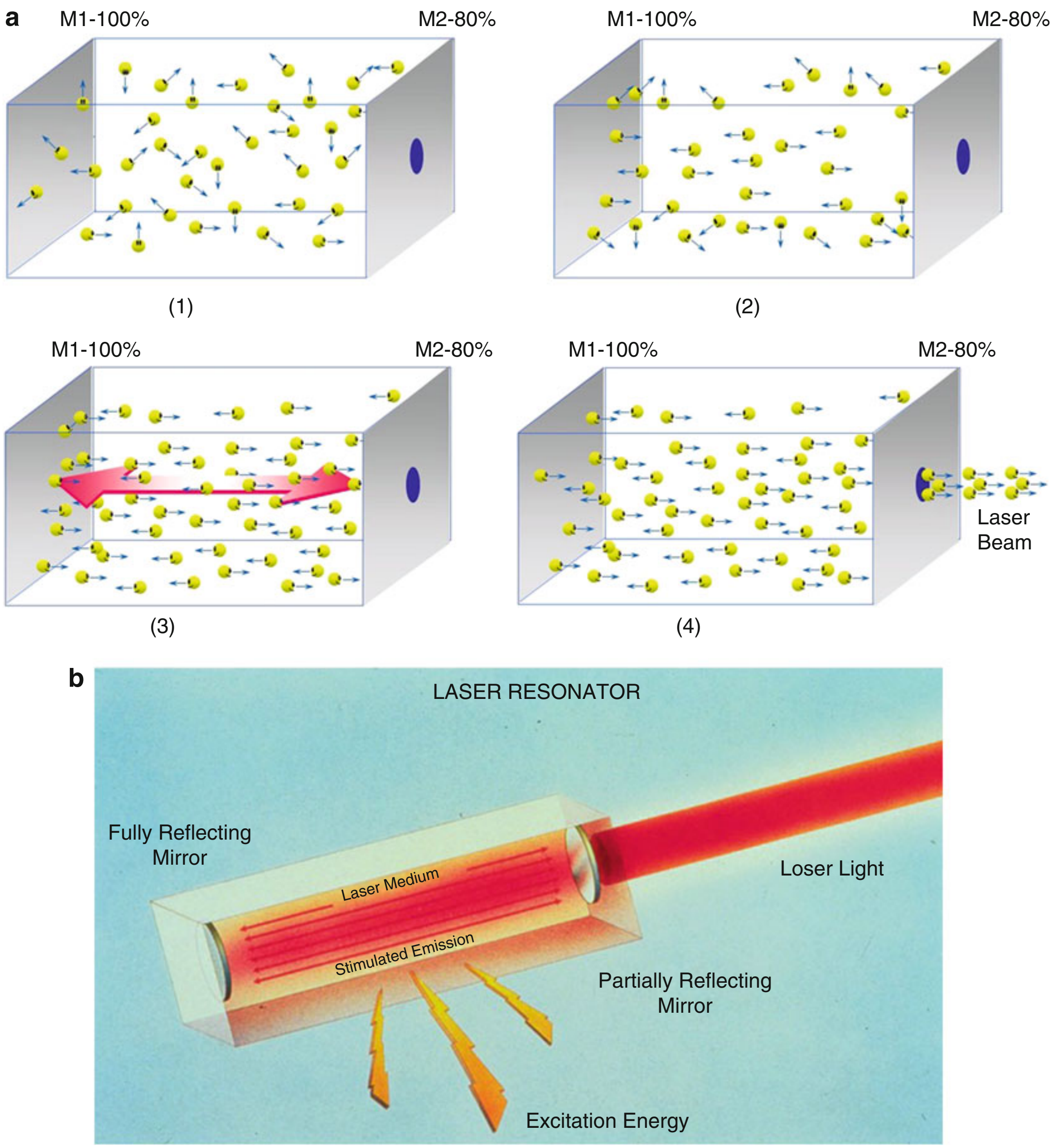

Fig. 5 (**a**) Light amplification and laser beam formation inside a laser resonator. M1 is the 100% reflection mirror and M2 is the 80% partial reflection mirror. The (*1*) and (*2*) are excited atoms that produce photons that begin to travel longitudinally along the resonator between the mirrors. The (*3*) and (*4*) are the photons traveling parallel to the axis of the resonator that stimulate new photons, producing the laser beam. (**b**) Schematic of the laser operation

Energy: is measured in Joules (J).
Power: is measured in Watts (W).

These are different parameters and they are related trough the following equation:

$$\text{Energy}(\text{J}) = \text{power}(\text{W}) \times \text{time}(\text{ sec })$$

Thus, energy is the amount of power delivered to the tissue in a given time, or the laser pulse duration. The thermal effect of the laser is highly localized. In this way, the physical quantity that governs the thermal response of the tissue is the amount of energy delivered to a certain area, the overall size of the application area or the “spot

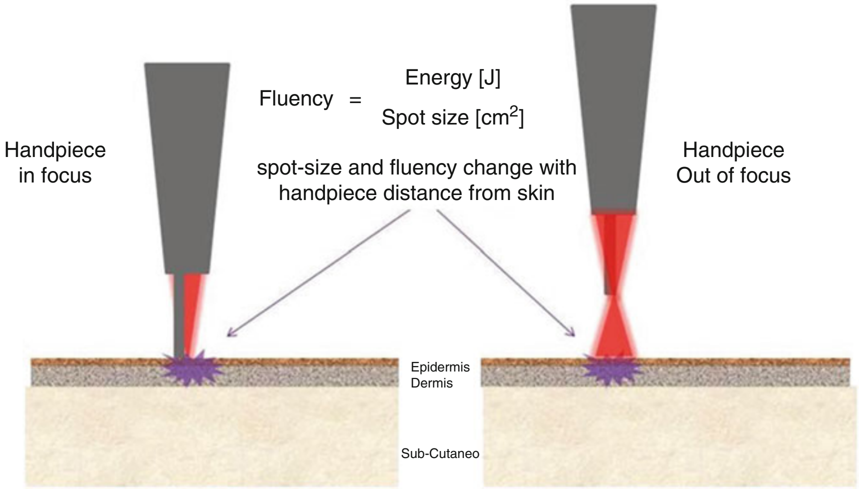

Fig. 6 Focused headpiece. Laser in focus: power density is at its maximum (vaporizing, cutting). Out of focus: power density is reduced (coagulation, milder treatment)

size" produced by the laser handpiece. Thus, the energy density or fluence is measured in J/cm^2:

$$\text{Fluence}\left(\text{J/cm}^2\right) = \text{Energy}(\text{J})/\text{Area}\left(\text{cm}^2\right)$$

The higher the fluence, the faster the temperature increases in the tissue and consequently the intensity of the desired effect. The effect of the treatment is achieved both by varying the laser output energy and the laser pulse duration, at the tissue application area. All commercial lasers allow us to change easily and continuously the energy.

For a fixed operating power, we can vary the fluence in the tissue by changing the application area (spot size – changing the lens that focuses the laser beam in the handpiece) or by varying the distance of the handpiece from the tissue in a "focused" handpiece.

When we work with light in focus (Fig. 6), the power density is at its maximum because all the energy of the laser is concentrated in a small focal point (usually of the order of 0.1–1 mm), called "spot size." At the focal point, it is possible to precisely cut the tissue and the application has its maximum effect. When we move the handpiece away from the tissue to a defocus, or out of focus position, the application area becomes larger reducing the power density (fluence) and increasing the temperature in the tissue. At this position, the effect becomes milder, producing a superficial effect of vaporization and coagulation (used in skin rejuvenation – skin resurfacing).

Another widely used laser handpiece is called "collimated." Here the laser beam remains parallel (collimated) and constant regardless of the distance from the tissue. It is used in hair removal systems and various types of skin treatment, such as tattoo and melasma removal (Fig. 7).

It is important to note how the cutting effect is controlled when using a laser. The surgeon is used to control the depth of the cut by the pressure exerted on the blade against the tissue. In the laser, as there is no mechanical contact with the tissue, the cut is determined by two factors:

1. Hand movement speed
2. Laser energy

The speed is linked to tissue exposure time, because if we keep the laser acting on a point indefinitely, it begins to vaporize layer upon layer of tissue increasing the depth of the cut. Thus, for a constant power if the surgeon moves the hand slowly, he or she will produce a deep cut. Likewise, for a movement with constant speed, the cutting will be deeper for a greater energy.

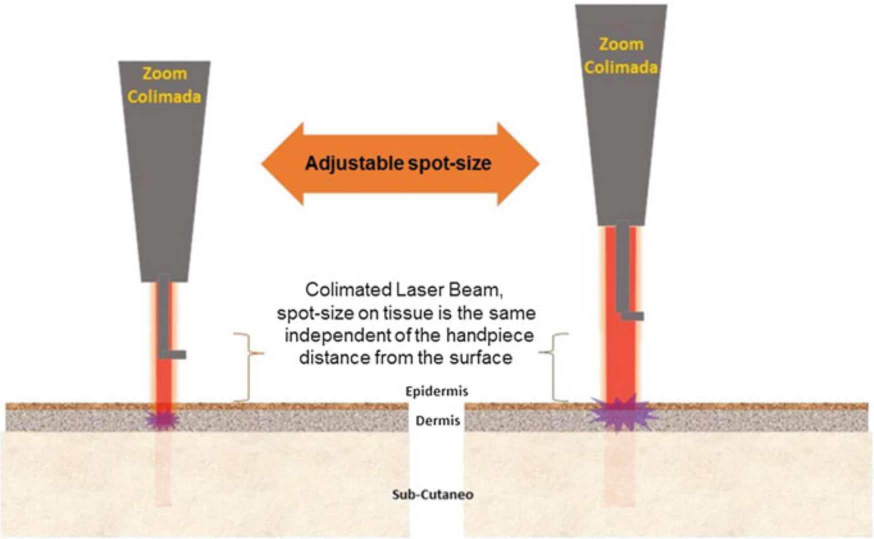

Fig. 7 Collimated handpiece. Regardless of the distance from the skin (touching or moving away), the spot size and fluence remain the same. Some handpieces have a zoom effect that allows the adjustment of the spot size

The laser exposure time also governs the amount of adjacent tissues which may be affected. Modern laser systems have mechanisms that quickly deliver energy to the tissue minimizing the thermal effect in adjacent areas. These mechanisms can be through ultrafast pulses (“ultrapulse” laser) or computerized rapid laser beam scanning systems (fractional scanners), used in skin rejuvenation treatments and more recently in fractional treatment systems. The “scanner” divides and moves the laser beam at high speed to position it over the skin minimizing damage to adjacent tissues. They are controlled by computer and can execute different types of scanning, with great precision and control over the amount of tissue being vaporized (Goldman and Fitzpatrick 1994; Arndt et al. 1997; Kulick 1998; Alster and Apfelberg 1999; Alster 1997).

Operating Modes of a Laser

Depending on the effect of the treatment we want to obtain on the tissue, laser systems can operate in the following modes (Boechat 2009; Raulin and Karsai 2011; Kaminsky Jedwab 2010; Sardana and Garg 2014):

1. **Continuous mode – CW**: In this mode of operation (also known as continuous wave), the laser stays on, just as a normal lamp, and emits a light beam of constant energy, as long as we keep the system powered by the foot switch or the power button on the handpiece (available on some devices). It is widely used in surgeries for coagulation or vaporization of tissue.
2. **Pulsed mode**: This mode works as if we turned a lamp on and off; the laser is pulsed electronically with the times and the intervals between pulses controlled by the equipment computer and selected via the panel. The repetition rate or frequency (given in Hz) of the laser pulse can also be programmed. Most lasers used in dermatology work with ultrafast pulses to vaporize the tissue faster than the thermal diffusion time of the skin in order to minimize damage to adjacent tissues, resulting in safe and effective treatments (Fig. 8).

According to the laser pulse duration, pulsed systems can be classified into:

(a) **Long pulses** – 0.001 s, millisecond (ms) 10^{-3} s
   i. Hair removal, varicose veins

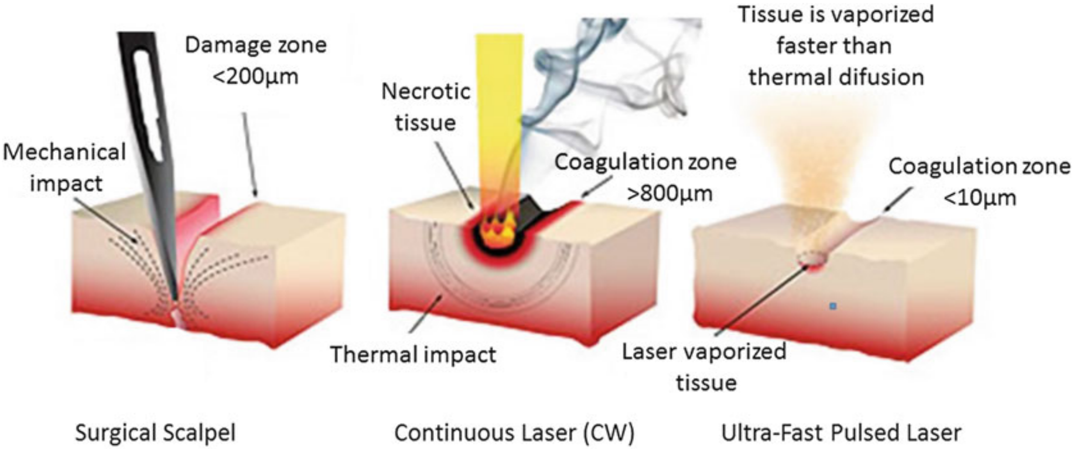

Fig. 8 Comparison of tissue laser cutting, showing continuous wave (*CW*) and ultrafast pulses that minimize the thermal damage to adjacent tissue

(b) **Quasi-CW** – 0.000001 s, microsecond (µs) 10^{-6} s
  i. Skin rejuvenation, onychomycosis, inflammatory acne

(c) **Q-switched** – 0.000000001, nanosecond (ns) 10^{-9} s
  i. Treatment of melasma, tattoo removal

(d) **Mode-locked** – 0.000000000001, picosecond (ps) 10^{-12} s
  i. Tattoo removal and pigmented lesions

(e) **Femto** – 0.000000000000001, femtosecond (fs) 10^{-15} s
  i. Refractive surgery in ophthalmology

Q-Switched: Nanosecond Lasers

This mode is achieved by placing an optical accessory inside the resonator, at the side of the laser crystal, whose goal is to pulse optically the light (Siegman 1986; Goldman 1967; Raulin and Karsai 2011). It is generally used in crystal lasers such as ruby, alexandrite, and Nd:YAG, described below. The goal is to accumulate the laser energy at very high levels and release it at extremely rapid pulses. The result is a very high-peak-power laser pulse (often higher than the common pulse), which can penetrate deep into the tissue, with minimal side effects. Then a shockwave-induced mechanical action caused by the impact of the laser pulse onto the target tissue causes its fragmentation. In the long- and quasi-CW-pulsed modes, the effect is purely thermal.

The classic application is in tattoo removal and the treatment of pigmented skin lesions such as dark circles, postinflammatory hyperpigmentation, and melasma (Goldman 1967; Reid and Muller 1978; Raulin et al. 1998; Chang et al. 1996; Shimbashi et al. 1997; Reid et al. 1990, 1983a; Stafford et al. 1995; Ogata 1997; Chan et al. 1999; Jeong et al. 2008; Mun et al. 2010; Grevelink et al. 1997).

Mode-Locked: Picosecond Lasers

To achieve picosecond pulses, a technique called “mode-locking” is used (Siegman 1986; Raulin and Karsai 2011; Sardana and Garg 2014). The base is a Q-switch system as described above, in which nonlinear effects of the Q-switch crystal are stimulated and modulated inside the resonator in order to create faster pulses with a technique in which only they are amplified. It is more commonly used in crystal lasers as alexandrite and Nd: YAG.

As we will see in the following chapter, the pulse duration governs the way in which light interacts with the tissue (selective photothermolysis), and by varying the pulse duration, we can completely change the laser application in dermatology.

Laser Types

All laser devices consist of the following parts (Siegman 1986; Goldman and Fitzpatrick 1994; Boechat 2009; Kaminsky Jedwab 2010):

1. The resonator/oscillator – with mirrors (total and partial reflectors) and active medium, which, when excited, produces the light and thus determines the wavelength
2. The excitation source (also called pumping) – which delivers power to the active medium producing the photons
3. Laser beam delivery system from the source to the hand of the operator
4. Handpiece, with focusing lens or a scanning system

The industry uses various elements in the manufacture of laser sources in order to cover a growing range of electromagnetic wavelengths. Today, we have ultraviolet lasers, visible light, and infrared. For this end, gases, liquids, crystals, fiber optics, and semiconductors (electronic components) are used.

The pumping of each element also varies; thus, electrical discharges, radio frequency, and light sources such as flash-lamps or even other lasers are used.

To carry the laser light from where it is generated in the resonator to the hand of the user who is making the application, various mechanisms are used depending on the wavelength and energy of the equipment. The most common are:

Articulated arm – a set of multiple mirrors positioned at the corners of articulated pipes to allow the freedom of movement in all directions (Fig. 9).

Optical fiber – thin waveguide with a core made of quartz covered with a thin layer called cladding, which is made of a slightly different material and encapsulated with plastic and metal coatings to give it flexibility. It delivers the laser beam by multiple internal reflections; that is, light enters the fiber, reflects on the core/cladding interface, and keeps moving until it exits the optical fiber. Note that at the output of the fiber, the laser beam has a wide divergence and is no longer collimated. In other words, the beam spreads, losing part of its coherence (Boechat et al. 1991, 1993) (Fig. 10).

Bellow we describe some typical commercial laser systems used in medicine, grouped according to the laser medium (Alster and Apfelberg 1999; Alster 1997; Boechat 2009; Raulin and Karsai 2011; Kaminsky Jedwab 2010; Sardana and Garg 2014).

Gas Lasers

Excimer

Gas molecules that exist only in the excited state, called “dimers,” form the excited medium; examples are molecules such as halogens combined with noble gases (ArF, KrF, XeCl, Xef). The word “excimer” is an abbreviation of the term “excited dimer.” The emission covers some wavelengths in the ultraviolet range such as 193 nm ArF, 222 nm KrCl, 248 nm KrF, and 308 nm XeCl. The pumping is usually made by electric discharge or the shock of electrons with gas molecules. Quartz optical fibers are used as beam delivery system. Since the wavelength is very small and carries a high energy, these lasers are widely used for high precision incisions or tissue ablation, such as in ophthalmic refractive surgery (myopia). In dermatology, this system has shown excellent results in the treatment of psoriasis and vitiligo (Zelickson et al. 1996; Guttman 2000).

Carbon Dioxide (CO_2)

The CO_2 is still one of the most used lasers in surgery, dermatology, and industrial applications. Its power may vary from a few KW up to MW in a continuous or pulsed manner. The laser medium is a mixture of gases including N_2 (nitrogen – 13–45%), He (helium – 60–85%), and CO_2 (1–9%). Pumping is achieved by high-voltage electric discharge or radio frequency (RF). The molecule of CO_2 is excited by mechanical shock with electrons, of the N_2 and He molecules. The wavelength is in the infrared range at 10,640 nm.

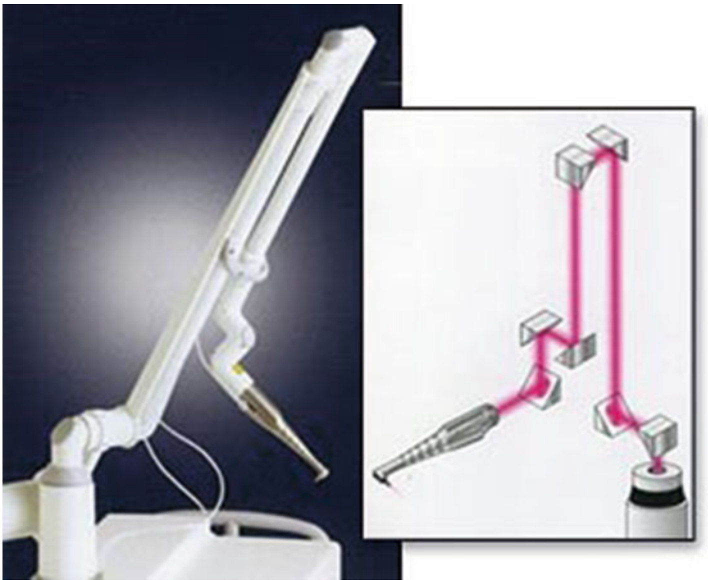

Fig. 9 Diagram of an articulated arm

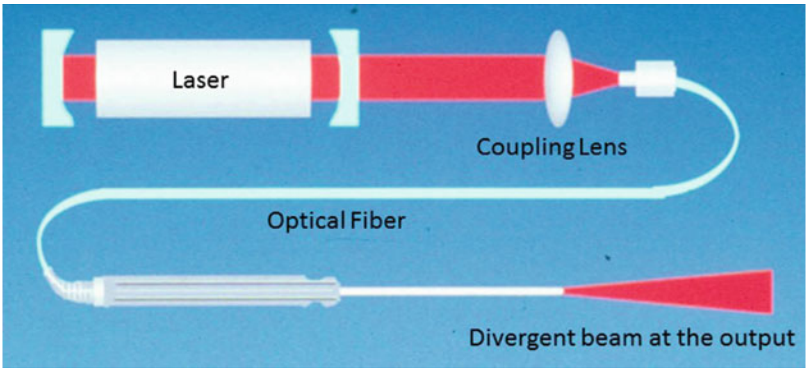

Fig. 10 Diagram of an optical fiber showing the beam divergence at the output

This is a relatively efficient laser (30% of electro-optical conversion), and because of that, it has low power consumption and maintenance. It uses an articulated arm and special dielectric-coated flexible hollow waveguides (Siegman 1986; Kulick 1998; Alster and Apfelberg 1999; Alster 1997; Lask 1995; Pitanguy et al. 1996) (Fig. 11).

Liquid Laser

Dye Laser

It uses a liquid Rhodamine solution (R6G), which is a fluorescent dye, as the laser medium. It is pumped by a flash-lamp or another laser. The wavelength may vary continuously from 300 to 1,000 nm, and the resonator can be tuned. It is most commonly used in yellow (585–600 nm). Its main application is the treatment of vascular lesions and inflammatory processes of the skin. It uses quartz optical fiber (Siegman 1986; Reichert 1998; Mcmillan et al. 1998; Reyes and Geronemus 1990) (Fig. 12).

Solid-State Laser (Crystal)

Figure 13 shows the schematics of the most common solid-state laser systems in the market. The mirrors, the laser rod (the crystal), and the flash-lamp, used for the pumping inside a cavity made of a coated elliptical reflecting material – usually

Fig. 11 RF-pumped CO_2 laser with articulated arm, eCO_2™ (Lutronic Inc.)

Fig. 12 Flash-lamp-pumped dye laser, Vbeam Perfecta™ (Syneron Candela)

ceramic or a large resistance metal such as gold – compose the resonator (Siegman 1986; Boechat 2009).

Ruby: $Cr^{3+}:Al_2O_3$

It was the first laser developed by Maiman in 1961 (Siegman 1986; Goldman and Fitzpatrick 1994; Arndt et al. 1997; Siegman 1986), but it was some time before this system started to be used in medicine. The medium is ionized ruby crystal. It is pumped by a flash-lamp. The wavelength is in the red range of 694 nm. The nature of the crystal requires high energy for pumping or high-power flash-lamps. It uses fiber optics and articulated arm for laser delivery. It is generally used for the treatment of pigmented lesions, hair, and tattoo removal (Goldman 1967; Reid and Muller 1978; Raulin et al. 1998; Chang et al. 1996; Shimbashi et al. 1997; Yang et al. 1996; Ono and Tateshita 1998; Reid et al. 1990, 1983a) (Fig. 14).

Alexandrite: $Cr:BeAl_2O_4$

The gain medium is chromium-doped chrysoberyl, the semiprecious stone alexandrite ionized. It is pumped by a flash-lamp. The wavelength is at the end of the red range (755 nm). It uses flexible optical fibers or an articulated arm. This crystal has better optical properties, which enables a faster and more efficient operation in a smaller device than the ruby. It is widely used for hair removal and treatment of pigmented lesions (Siegman 1986; Finkel et al. 1997; Stafford et al. 1995; Chan et al. 1999; Alster 1997) (Fig. 15).

YAG Family

The YAG abbreviation is short for yttrium aluminum garnet, which is a synthetic crystalline structure serving as host to the ion that will produce the radiation with the desired wavelength. It is pumped by laser diodes or a flash-lamp, and it works in the near-infrared spectrum. It uses optical fiber and in some cases the articulated arm (high-energy pulsed laser – Q-switched) as the beam delivery system. The most common are (Siegman 1986; Goldman and Fitzpatrick 1994; Kulick 1998; Wong and Goh 1998; Ogata 1997; Chan et al. 1999; Boechat 2009; Raulin and Karsai 2011; Kaminsky Jedwab 2010):

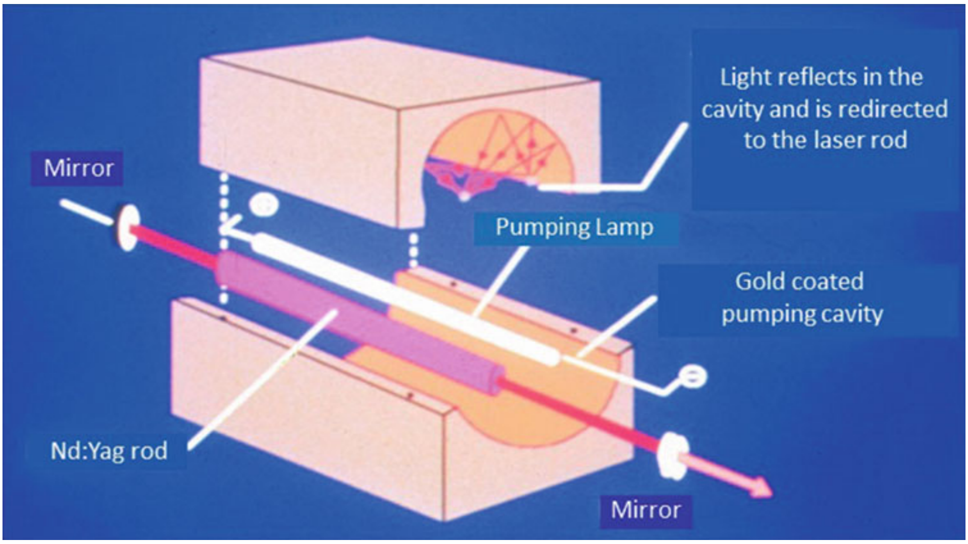

Fig. 13 Schematics of a typical laser using a crystal rod

Fig. 14 Ruby laser with an articulated arm (Asclepion Laser Technologies)

Fig. 15 Alexandrite laser, GentleLase™ (Syneron Candela)

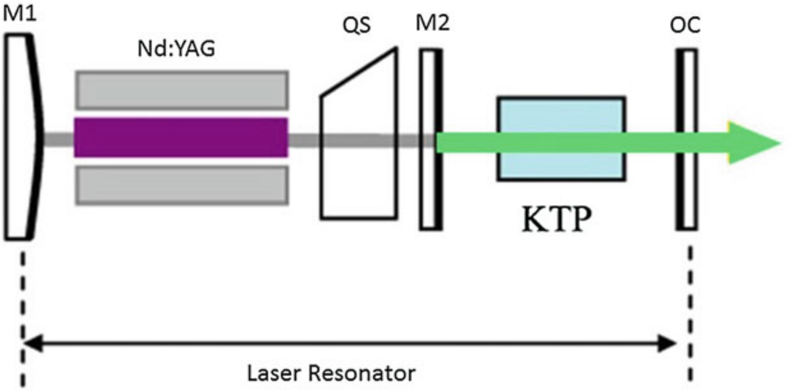

Fig. 16 Schematics of a KTP laser pumped by a Q-switched Nd:YAG laser. M1 is the 100% reflector mirror; M2 is the partial reflector output coupler for the Nd:YAG pumping laser; *QS* Q-switch, *KTP* the KTP crystal, *OC* output coupler and wavelength selector for 1,064 nm and 532 nm

- ***Nd*:*YAG*** – it uses the neodymium ion, with wavelengths of 1,064 nm and 1,320 nm, which is used for non-ablative skin rejuvenation (Muccini et al. 1998; Goldberg 1999, 2000).
- ***Nd*:*YAG*/*KTP*** – by placing a second crystal in the laser resonator, in general the "famous" potassium-titanium-phosphate (KTP), it generates the frequency-doubled Nd:YAG laser with a green wavelength at 532 nm. It is used for removal of superficial pigmented and vascular lesions (Figs. 16 and 17).
- ***Nd*:*YAG*/*KTP* + *handpiece with crystal dye*** – a solid-state fluorescent dye handpiece can still be added to these lasers in order to obtain different wavelengths, such as 595 nm (yellow) and 650 nm (red), thus making the machine extremely versatile for the treatment of pigmented lesions and the removal of light-colored tattoos at different depths (Fig. 18).
- ***Ho*:*YAG*** – it uses holmium ions, with wavelength of 2,100 nm. It is excellent for treatments in bone and cartilage and for the fragmentation of kidney stones.
- ***Er*:*YAG*** – it uses erbium ions, with wavelength of 2,940 nm. It is well-known for its use in "skin resurfacing" (skin rejuvenation) (Fleming 1999; Weinstein 1998) (Fig. 19).
- ***Tm*:*YAG*** – it uses thulium ions, with wavelength of 1,927 nm. It is used for non-ablative skin rejuvenation with a more superficial action.

Fig. 17 Laser system Spectra XT™ with two wavelengths: Nd:YAG (1,064 nm) and KTP (532 nm), Lutronic Inc.

Nd:YAP

It uses neodymium ions in yttrium aluminum perovskite crystal, with wavelength of 1,340 nm. It is used for non-ablative skin rejuvenation and chronic inflammatory diseases such as hidradenitis (Milanic and Majaron 2013; Antonio et al. 2015).

Fig. 18 Crystal dye handpieces, laser Spectra XT™ (Lutronic Inc.)

Fig. 19 Er:YAG laser system, with articulated arm for ablative skin rejuvenation (Fotona)

Fig. 20 Fractional Er:glass laser system, Matisse™ (Quanta System)

Er:Glass

The gain medium is changed for crystal glass, which serves as host for the erbium ion. The wavelength shifts to 1,540 nm, in the near infrared. It is used for deeper skin rejuvenation and employed in fractional laser systems (Mordon et al. 2000) (Fig. 20).

Er:YSGG

The gain medium is similar to the YAG crystal, and it uses the erbium ion in an yttrium scandium gallium garnet (YSGG) host. The wavelength is also in the near infrared, 2,790 nm, used in the Pearl™ handpiece of Cutera. The main application is fractional skin rejuvenation. It is an alternative to the Er:YAG laser skin resurfacing.

Semiconductor Laser

- **Diode** – the laser medium is a semiconductor, i.e., an electronic component. It is pumped by electric current. The changing of the semiconductor achieves a wide range of wavelengths ranging from the visible, 450 nm, to the near infrared, 1,400 nm. The most common are AlGaAs (aluminum gallium arsenide) with wavelengths from red to near infrared, 620–900 nm, and GaAs (gallium arsenide) in the near infrared, 830–920 nm. It has a very efficient electro-optical conversion (greater than 50%); thus, generally it is a small and greatly simplified operation system. It uses optical fibers or simply free, handheld devices. Some equipment manufacturers provide systems with one or more laser diodes with different wavelengths, increasing the flexibility of the system. It is widely used for hair removal, non-ablative skin rejuvenation, and treatment of vascular lesions. It is also used for pumping other lasers such as Nd:YAG, Nd:YAG/KTP, and fiber-optic lasers, as we will see below (Siegman 1986; Goldberg 2000; Ross and Hardway 2000; Lou et al. 2000) (Fig. 21).

Fig. 21 LightSheer Duet diode laser, 810 nm (Lumenis)

Optical Fiber Laser

Extremely robust, long-lasting, and highly reliable, this technology employed in undersea optical telecommunications cables has found an application in medicine in the development of fractional lasers (Manstein et al. 2004; Geronemus 2006; Raulin and Karsai 2011).

- **Y**, **Er**:**fiber** – the gain medium is a quartz optical fiber measuring only 150 μm in diameter, containing erbium and yttrium ions. It is pumped by laser diodes. The wavelength is 1,550 nm. The system does not need optical components such as mirrors, output couplers, flash-lamps, and cooling system, which significantly reduces the need and cost of maintenance. This new technology produces microscopic focal points on the skin of the order of 100 μm (approximately the thickness of a human hair), since the light source is also a microscopic fiber, leading to the advent of fractional skin treatment (Fig. 22).

LED: Light-Emitting Diode

LEDs are electronic components, or semiconductor diodes, that emit light when stimulated by electric current. They may be considered as relating to laser diodes, since they are manufactured with the same materials, as GaAs, GaAlAs, and GaInPAs, and thus provide the same wavelengths. However, they do not have the light amplification effect produced by a laser resonator system. In this way, an incoherent monochromatic light is produced that diverges in various directions just as a lamp of low intensity (Boechat 2009; Raulin and Karsai 2011; Kaminsky Jedwab 2010).

In order to concentrate and direct the emitted light, they are manufactured with a parabolic plastic housing, which functions as a small lens (Fig. 23).

Fig. 22 Optical fiber laser, Mosaic™ (Lutronic Inc.)

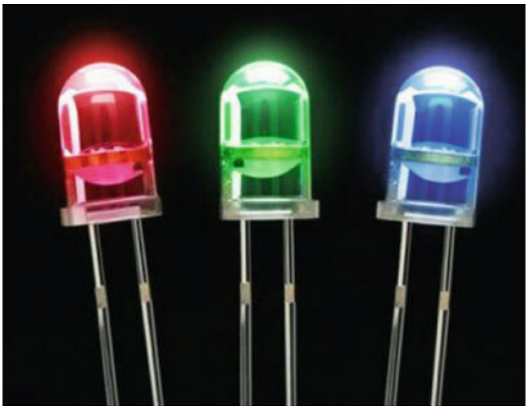

Fig. 23 Example of LEDs

LED treatment systems use panels made of 1,000–2,000 components in order to extend and optimize the application area. Depending on the application or treatment, it is possible to change the panel to a different wavelength. Some manufacturers have integrated LEDs with different wavelengths on the same panel thus avoiding the need to change them (Fig. 24a, b).

Some of the most common applications are in the biomodulation of cells, described below and in the following chapters, such as anti-inflammatory effects and improved wound healing. It is also used in photodynamic therapy and teeth whitening.

Intense Pulsed Light

It is a system that employs a flash-lamp for many applications, but it is not a laser light source, pulsed light, or intense pulsed light – IPL. Dr. Shimon Eckhouse at ESC Medical in Israel developed this concept, in the nineties (Boechat 2009; Raulin and Karsai 2011; Kaminsky Jedwab 2010).

It uses an electronically controlled intense flash-lamp. For this reason, it has distinct characteristics from a laser source:

(a) **Polychromatic**: it emits a broad spectrum of wavelengths, generally in the range from 400 to 1,200 nm. It uses band-pass filters placed in front of the lamp for wavelength selection. These filters remove a band of wavelengths, in general those below the filter specification, letting through all the wavelengths above it. Some machines use a more complex filter, which narrows the emission at a range of wavelengths, as illustrated in

Fig. 24 (**a**) LED panel, Hygialux™ (KLD). (**b**) LED panels with different wavelengths (KLD)

Fig. 25 a–c. Even with a narrow emission spectrum limited by the filters, the emitted energy disperse within several wavelengths, that is those that will be absorbed by the tissue to be treated and others that will have no effect. Thus, the selectivity and effectiveness of the treatment are reduced as compared with a laser that has 100% of the energy concentrated in a single wavelength (monochromatic).

(b) **Incoherent**: Different from a laser source, the IPL energy is emitted in all directions; it spreads. Mirrored surfaces placed behind the lamp, similar to reflectors used in car headlights, concentrate and direct the light. It will have a more superficial and mild effect on the tissue because it is less intense than laser light. The application will also be less painful.

The multiplicity of emitted wavelengths makes these systems very versatile, being able to perform several applications such as in hair removal, pigmented lesions, non-ablative rejuvenation, and vascular lesions, by simply changing the filter and pulse duration (Fig. 26).

These systems generally have a fixed pulse duration already set by the manufacturer depending on the application. To change the pulse duration, in general, it is necessary to change the entire handpiece. Pulse duration is restricted to the range of milliseconds because of the lamp characteristics; however, it suits most skin applications.

Treatment Platforms

Following the trend of the market to produce increasingly compact systems, which provide various applications, the laser industry has developed the concept of multi-application platform. These systems consist of a base (platform) that carries the energy source and cooling system. Then several handpieces can be connected to the base providing different applications. Each handpiece may contain an IPL or a laser system. The most frequent applications are hair removal, skin rejuvenation, treatment of pigmented and vascular lesions, and tattoo removal (Raulin and Karsai 2011; Kaminsky Jedwab 2010; Sardana and Garg 2014).

These treatment platforms became very popular because of the excellent cost/benefit and versatile combination of intense pulsed light and laser in the same equipment. There are also platforms that have only lasers, or only IPL, and others that added a RF handpiece for skin tightening (Fig. 27).

After becoming familiar with these technologies and their operating principles, a question comes to mind: when and how to use each of these systems?

The application of each laser, IPL, or LED in dermatology will depend on the response of the tissue to the wavelength being used.

Light-Tissue Interaction

Light can interact with living tissue in the following forms (Anderson and Parrish 1981; Goldman and Fitzpatrick 1994; Arndt et al. 1997; Kulick 1998):

Photothermal: light energy is absorbed by the target tissue (chromophore) and transformed into heat, causing coagulation or vaporization.

Photomechanical: fragmentation by mechanical effect, as in the Q-switch described above.

Photochemical:

1. Direct breaking of chemical bonds between atoms of a molecule produced by, for example, an ultraviolet excimer laser when sculpting a cornea, thus with great accuracy.
2. Light activates a chemical reaction that produces reactive free radicals, as in photodynamic therapy (PDT), described in a following chapter.

Photobiomodulation: light is used to modulate intra- and intercellular activities. It employs low-power laser and LED panels. It has anti-inflammatory action and the effects of wound healing and tissue regeneration (Lopes 1999).

Selective photothermolysis: it is the art of combining wavelength, pulse duration, and energy to obtain the desired effect on the target tissue preserving adjacent areas, as described below.

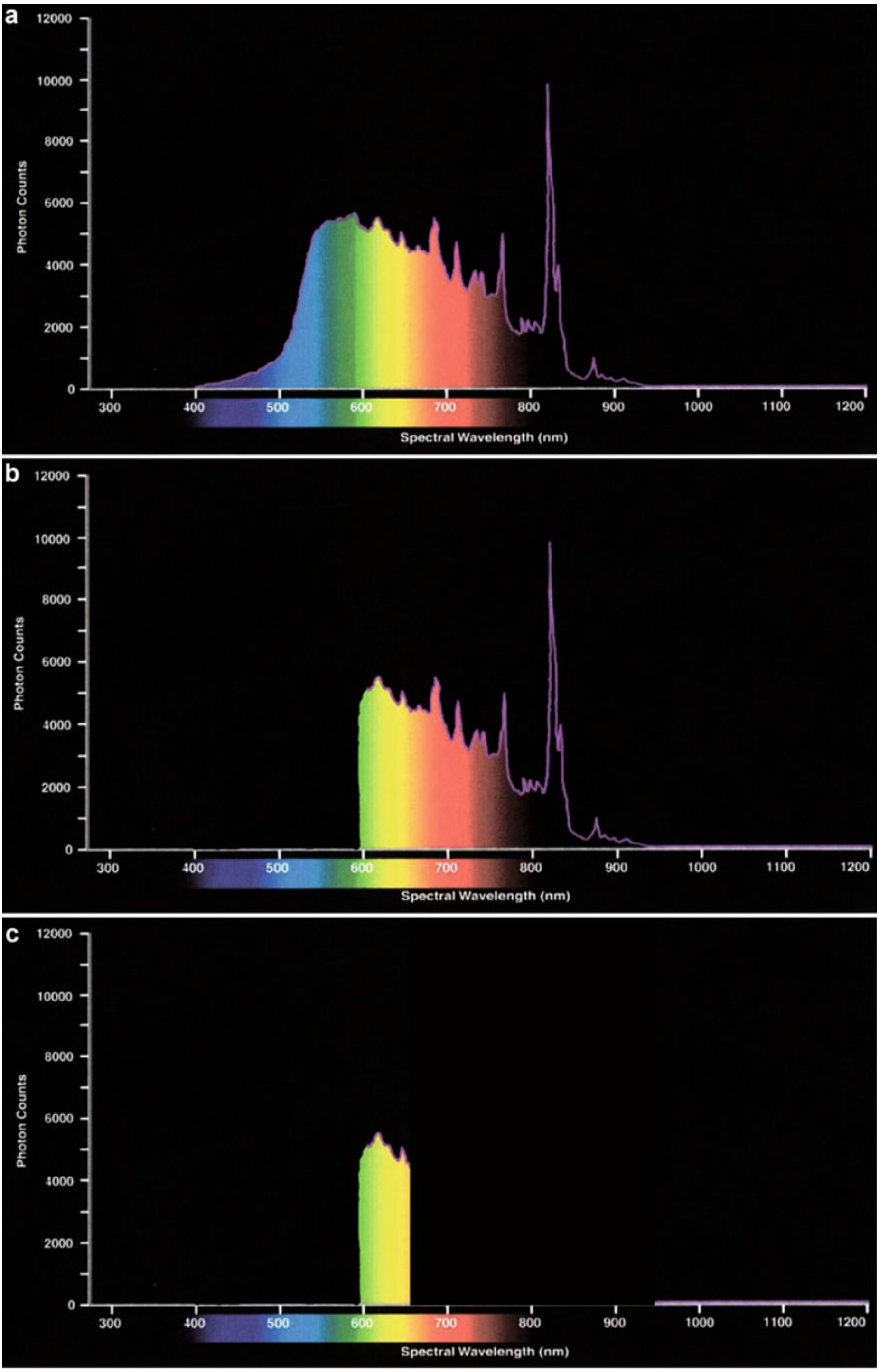

Fig. 25 (**a**) General output spectrum of an IPL, (**b**) with a single 570 nm cut filter and (**c**) with a band-pass filter that limits even further the output spectrum

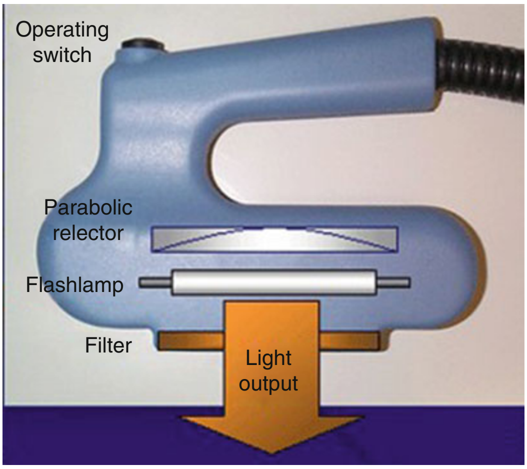

Fig. 26 Schematics of an intense pulsed light – IPL (Lumenis)

Fig. 27 Treatment platform Harmony™ with several handpieces (Alma Lasers)

When a beam of light hits the tissue, it is (Fig. 28) partially transmitted, reflected, spread (scattering), or absorbed.

Laser light will only produce a therapeutic effect if the target tissue is “in tune” with the energy that is being used, as in a mobile phone. At any given time, there are thousands of mobile phone waves passing where we are, but the phone does not ring. It will only be triggered when the emitted wave is in tune with the device. Similarly, we can place several wavelengths of light in the skin, but the target tissue will absorb only a specific light. In particular, the energy deposited by the most commonly used lasers in medicine is transformed into heat and thus produces a temperature increase on the chromophore.

The laser parameter that most influences the absorption factor, also called the “tuning” effect, is the wavelength of the light (its color; its frequency). Each part of our organism or component of our skin responds differently or has affinity to a particular wavelength. Certain tissues are transparent to a particular laser; others absorb it completely. Therefore, we can induce the necessary thermal effect to treat it selectively at a specific point without affecting the surrounding tissue, giving rise to the phenomenon of the “selective photothermolysis” theory developed by Dr. Rox Anderson et al. in Boston, USA (Anderson and Parrish 1981, 1983; Goldman and Fitzpatrick 1994).

The graph of Fig. 29 represents the fundamental result of the publication of Anderson et al. (Anderson and Parrish 1981; 1983). It shows the variation with wavelength of the absorption coefficient of certain skin components, such as melanin, hemoglobin, and water molecule. We can see that melanin has a high absorption for lasers in the visible range, such as green (KTP), which can be used, for example, in the treatment of pigmented lesions. Hemoglobin has an absorption peak in the range of yellow light (dye laser), making it a good option for treating vascular lesions. The ruby laser, in the range of red light, is well absorbed by the melanin and dark pigment in the skin. On the other hand, it is positioned at a minimum for hemoglobin absorption, which explains in part the difficulty that these systems have to remove red pigments in the treatment of tattoos and vascular lesions (low coagulation effect).

When the light of these lasers enters the skin in fast pulses, or rather ideal pulses, it is able to cross

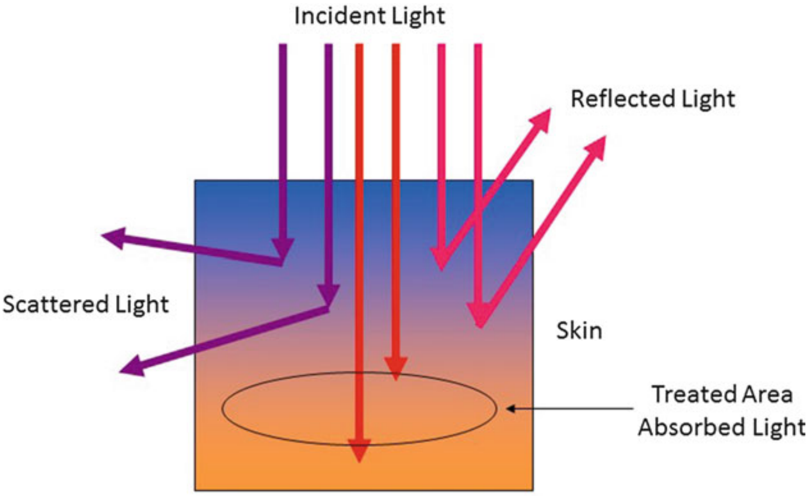

Fig. 28 Light-tissue interaction

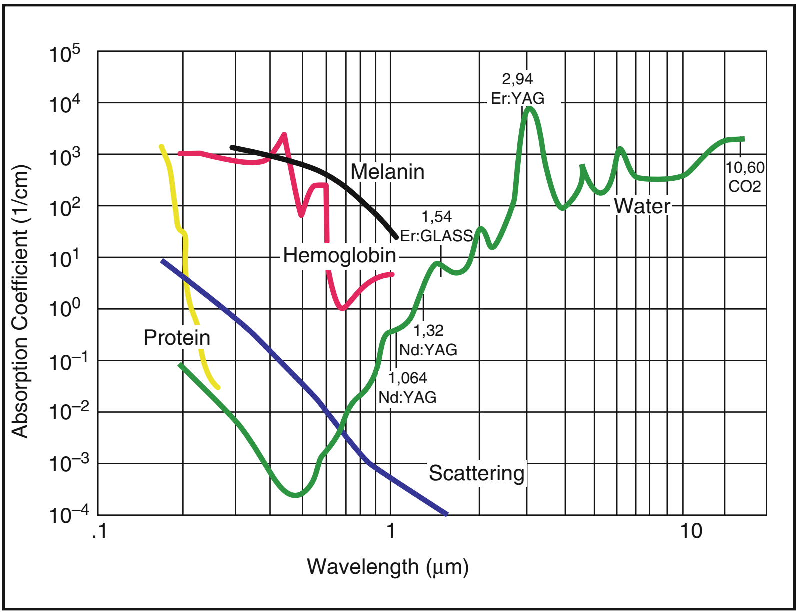

Fig. 29 Curve of the absorption coefficient of some tissue components as a function of wavelength, pointing out the most popular laser systems

the skin without causing any damage and is absorbed only by the target tissue with which it has affinity. These components are referred to in the literature as “chromophores.”

We also note from the graph that the absorption of melanin in the visible and near infrared (invisible) is very wide which allows for a number of different lasers to be used effectively for treating pigmented lesions and hair removal, such as the 810 nm diode laser and 1,064 nm Nd:YAG. Because of the its longer wavelength, the Nd:YAG penetrates deeper in the skin, as described below, and its absorption coefficient for melanin is lower when compared to visible lasers, such as green. These are properties that make these lasers suitable for a variety of treatments, since they present reduced risk of damage of the skin surface, because of the absorption of melanin, and are effective for dermis treatments such as deep vascular lesions and melasma.

The Er:YAG (2,940 nm) and CO_2 (10,600 nm), in the infrared, have high absorption coefficients for water molecule. As water is the major component of the cellular structures, its interaction with these wavelengths is predominant. Therefore, the first layers of cells rapidly absorb the energy from these lasers increasing their temperature to the vaporization level, making it an excellent tool for cutting or precise and superficial tissue removal, such as in laser skin resurfacing or fractional laser skin resurfacing. The Er:YAG laser wavelength is at the peak of water absorption, with a coefficient at least ten times higher than the CO_2 laser. Since its light is more rapidly absorbed, the energy penetrates less, what makes it have a more superficial action compared to CO_2. The treatment will also have lees thermal effect being gentler to the skin (Chernoff et al. 1995; Alster et al. 1999; Weinstein 1998).

Another important aspect of light-tissue interaction is the laser pulse duration (pulse length or exposure time). This must be such that the energy produces an increase in temperature that is confined (concentrated) to the target tissue, with minimal dispersion to the surrounding areas. In other words, the laser pulse duration has to be long enough to increase the temperature on the target tissue up to its destruction level while being short enough not to irradiate heat to the surrounding tissue. A similar situation happens when we want to verify if the iron is hot enough for ironing clothes. Usually, we place the finger on the iron for enough time to check that it is hot, but remove it very fast to guarantee that we do not burn it.

In order to achieve the correct pulse duration, we need to observe the thermal relaxation time (TRT) of the target tissue.

From what is discussed above, the basic principles of selective photothermolysis are (Anderson and Parrish 1983; Goldman and Fitzpatrick 1994; Waldorf et al. 1997; Klavuhn 2000):

(a) **Ideal wavelength** that is absorbed only by the target tissue or chromophore
(b) **Ideal pulse duration** that should be sufficient to produce the desired effect on any target tissue, but fast enough to cause minimal effect on the surrounding tissues, i.e., confining the energy in the chromophore
(c) **Energy** enough to reach the treatment effect

In summary, the vast majority of treatments in photomedicine happen as follows:

1. Light is absorbed by the target tissue or chromophore.
2. The absorption of light causes a selective heating of the target while preserving the surrounding tissues.
3. The chromophore selective heating causes its coagulation or vaporization, reaching the goal of the treatment.

Light Penetration Depth

Giving great importance to the effectiveness of the treatment, light penetration depth is primarily governed by the wavelength, observing the following factors (Anderson and Parrish 1981; Raulin and Karsai 2011; Sardana and Garg 2014; Lapidoth and Halachmi 2015):

1. Scattering of light in the visible part of the spectrum.
2. Absorption by water in skin cells, particularly the epidermal ones on the near-infrared wavelength range.
3. For a given wavelength, the higher is the energy, the deeper the energy will reach.

Going back to the graph of absorption coefficient of Fig. 29, we see that light scattering (blue curve) becomes stronger for smaller wavelengths on the visible range. Therefore, for this part of the spectrum, regardless of the energy used, penetration is usually very small as shown in the graph of Fig. 30. The scattering effect begins to reduce in red light (700 nm) and practically disappears in the near-infrared range, around 900–1,100 nm, which allows these wavelengths to penetrate deeply into the tissue. After 1,200 nm, the absorption of the water in the chromophore present in abundance in the skin cells starts to become significant, again reducing the light penetration.

As it penetrates the skin, light energy is absorbed and scattered along the way, decreasing

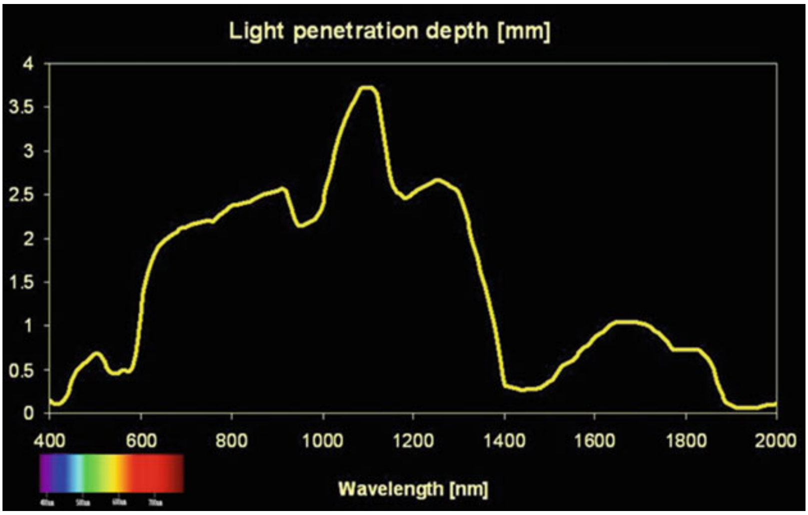

Fig. 30 Light penetration depth as a function of the wavelength

the intensity until it disappears. The power distribution along the light path in the tissue will reduce as it penetrates the skin. The energy in the surface is always higher than at any point within the tissue. Therefore, for a given wavelength, light with higher energy at the surface will have a slight increase in tissue penetration.

In summary, visible wavelengths are ideal for the treatment of superficial lesions such as spots or port-wine stains. It is common to observe in the treatment of superficial pigmented lesions that some spots do not clear completely. This can indicate that part of the spot is located on a deeper layer where light does not reach.

Wavelengths on the range of 900–1,100 nm should be used for the treatment of deep lesions such as varicose veins or hemangiomas and dermal melasma.

Another mechanism can control the light penetration depth. For a given wavelength and fluence (energy/application area), it is possible to achieve a greater energy penetration by increasing the spot size. Figure 31 illustrates the effect of the spot size on light penetration. Using a small spot size, it is not possible to achieve the concentration of light deep into the skin because of the scattering. For a larger spot size, the dispersion is the same, but it compensates the scattering effect by achieving a greater energy concentration deeper into the skin. Therefore, the larger the spot size, the greater the energy concentration or the deeper the penetration. This effect is important, for example, in laser hair removal, treatment of dermal melasma, and tattoo removal (Raulin and Karsai 2011; Kaminsky Jedwab 2010; Sardana and Garg 2014).

Fractional Laser Systems

To appreciate the revolution introduced by the fractional laser technology, let us imagine a patient who seeks an aesthetic improvement of the skin as a family photograph that needs some finishing touches. Today, a photograph is digitally altered pixel by pixel, to improve the appearance of objects in the image. Likewise, damaged paintings are restored gently in a small area at a time.

This same concept is employed in systems that use the fractional photothermolysis technology. The laser produces microscopic thermal injury called microthermal zones (MTZ), approximately 100–150 μm in diameter – the thickness of a human hair – and depth from 0.2 to 2.4 mm (IPL devices in general achieve a maximum of 0.3 mm below the surface). These MTZs are surrounded by healthy tissue that is not affected and will help in the recovery of the micro-damaged area. The surrounding tissue will also be mobilized in the overall skin regeneration process. The resulting rejuvenation effect is comparable to deep

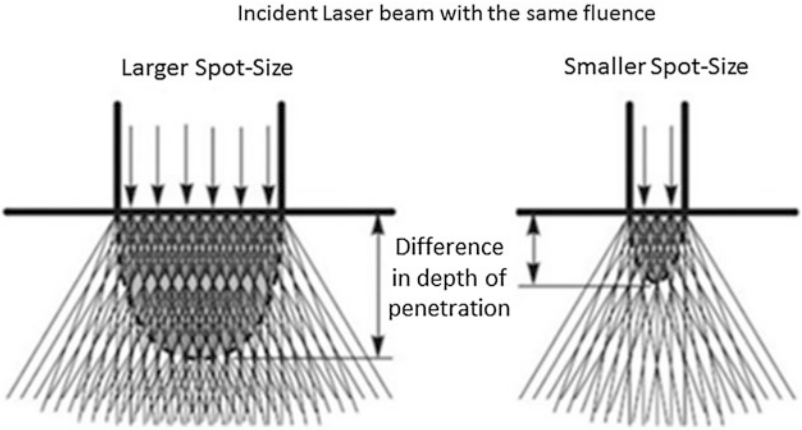

Fig. 31 Spot size effect on the penetration depth of a laser beam with the same fluence

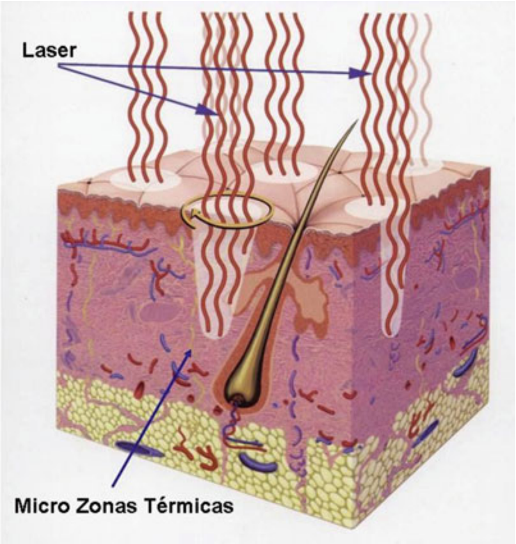

Fig. 32 The science of fractional photothermolysis

chemical peels or dermal mechanical abrasion, but with minimal side effects and little downtime (Fig. 32).

An intelligent scanning system (optical scanners) located on the handpiece ensures the even distribution of MTZs. The operator can choose directly in the laser panel the amount of MTZs that will be put on the skin or the percentage of the total skin area that will be stimulated, controlling the aggressiveness of the treatment. More MTZs means greater stimulus, being more aggressive the application and consequently showing more results. This leads to an application control that hitherto did not exist in dermatological treatments.

The method was developed by the parents of selective photothermolysis, Doctors Rox Anderson and Dieter Manstein, at the Wellman Laboratories in Boston, USA. The first fractional laser system, the Fraxel SR, was shown by Reliant Technologies Inc. in the Congress of the American Academy of Laser (American Society for Laser in Medicine and Surgery – ASLMS) in April 2004 (Laubach et al. 2005; Geronemus 2006; Raulin and Karsai 2011; Munavalli et al. 2005; Khan et al. 2005).

The system follows the principles of selective photothermolysis with wavelength in the 1,550 nm range, where the water of the chromophore is present in the skin cells. In its original design, the fractional systems perform a non-ablative treatment, preserving the skin surface, and the temperature of the tissue increases only up to the coagulation point, producing microthermal zones. Treatment takes three to five monthly sessions.

Beyond the minimum recovery time, the advantages of this treatment include the possibility to use the laser to treat other regions of the body besides the face with safety and efficacy and to remove deep pigmented lesions, and also there are surprising results on the improvement of unaesthetic and acne scars. The following chapters will discuss in detail applications of fractional treatment.

Some commercial non-ablative fractional systems are:

Fraxel re:Store – 1,550 nm wavelength, Er:fiber laser. It has a handpiece with an intelligent continuous scanning system that measures the speed of the application of the operator to distribute the MTZs on the skin homogeneously.

Palomar Lux1540 – it has a fractional handpiece of the Palomar StarLux platform, which employs an Er:glass laser. It uses a fixed filter at the output to split the beam and to generate the fractional effect. Thus, the number of MTZs and application area is fixed.

Lutronic Mosaic – it is a fractional system from Lutronic Inc., which is a Korean company that also employs an Er:fiber laser with wavelength at 1,550 nm. It uses the intelligent scanner at the handpiece; thus, it is possible to choose the number of MTZs (density of the treatment), and the application can be in a static or continuous scan mode, as Fraxel (Fig. 22).

The great success of the fractional technology led to the diversification and improvement of the method originating the ablative fractional treatment. The laser drills micro-holes with controlled depth in the skin, with a thin tissue coagulation zone around them. The surface is damaged producing small crusts and more persistent erythema. The recovery time is longer, and there are restrictions on the skin type and body areas to be treated.

The ablative fractional treatment brought back the CO_2 laser to the rejuvenation scenery because it gave control, safety, and less restriction to the previous efficient CO_2 laser skin resurfacing that still remains the gold standard of skin rejuvenation. Another advantage is that it can also be used for precise cuts and vaporization in minor surgeries.

Bellow, we show some examples of commercial fractional ablative lasers:

Lutronic eCO$_2$ – it is a CO_2 fractional laser with static and dynamic scanning system (Fig. 7). It is possible to program the diameter and density of MTZs.

Fraxel re:pair – it is a CO_2 laser, which uses the same fractional technology as the non-ablative Fraxel re:Store with an intelligent continuous scanning system.

Lumenis Total Active FX – it also uses a CO_2 laser with intelligent scanners, which allow for static and dynamic scanning modes. The diameter and density of MTZs can be programed.

Deka SmartXide^2 DOT/RF – it is a CO_2 laser with scanners and radio-frequency (RF) technology integrated in the handpiece.

Alma Pixel CO$_2$ – it is a CO_2 laser with an array of micro-lenses on the tip to split the beam and to produce the fractional effect. The number and diameter of MTZs are fixed although it offers handpieces with different sizes.

Alma Pixel Handpiece – it is a fractional handpiece from the multiplatform Harmony employing an Er:YAG wavelength of 2,940 nm and a filter effect to split the laser beam and to produce the fractional effect. The MTZs are thicker than in the other devices, of the order of millimeters in diameter, and more superficial, reach only the epidermal layer, because of the wavelength and energy of the system.

Radio Frequency

Radio frequency (RF) consists of a high-frequency electric current, of the order of 1 MHz, and has been used in medicine for several years. Just for comparison, household appliances, such as TVs and refrigerators, work with 50 or 60 Hz, which are low frequencies.

Going back to Fig. 1, the chart of the electromagnetic spectrum, we see that RF occupies the kHz to GHz range, used for radio communication, which gave it its name. Medical equipment uses a portion of the narrow band of this range – from 200 kHz to 40 MHz – in different applications. In this frequency range, the effects of stimulation of nerves and muscles decrease, and thus, the energy can be applied gently to achieve different levels of tissue heating (Lapidoth and Halachmi 2015).

The RF systems can be “monopolar,” “bipolar,” “multipolar,” and “unipolar” (Lapidoth and Halachmi 2015).

Monopolar RF

These devices use an active electrode to apply the RF to the area of treatment, in the form of a handpiece, and a return electrode, usually in the form of a grounding pad with a large contact area, which is placed far from the treatment zone (Fig. 33).

A high RF current density is created at the active electrode, and the current diverges as it penetrates the tissue going toward the large return electrode. Therefore, the heat is generated near the active electrode, and it does not depend on the size, shape, or position of the return electrode.

The RF current diverges rapidly away from the electrode; thus, the heating effect decreases. At a distance equal to the electrode size, heating becomes insignificant. The heat zone can be estimated as half the size of the electrode. Therefore by controlling the RF power and the geometry and size of the electrode, it is possible to control the penetration depth and the effect on the tissue.

Popular monopolar system uses are in surgery for the cutting and coagulation of blood vessels. In dermatology, there is the application for skin tightening and collagen remodeling, as the geometry of the large electrode targets the deeper tissues of the dermis (Fig. 34).

Bipolar RF

This configuration uses two electrodes which are placed close to each other and in contact with the treatment zone. The RF current flows between the electrodes and does not spread to other parts of the body as in the monopolar configuration. This geometry creates a more uniform heating at the treatment zone compared to the monopolar devices (Fig. 35).

Both electrodes create an equal thermal effect near them, and the divergence of the RF current is reduced because of the small distance between them. Therefore, most of the heat is concentrated

Fig. 33 Basic configuration of a monopolar device

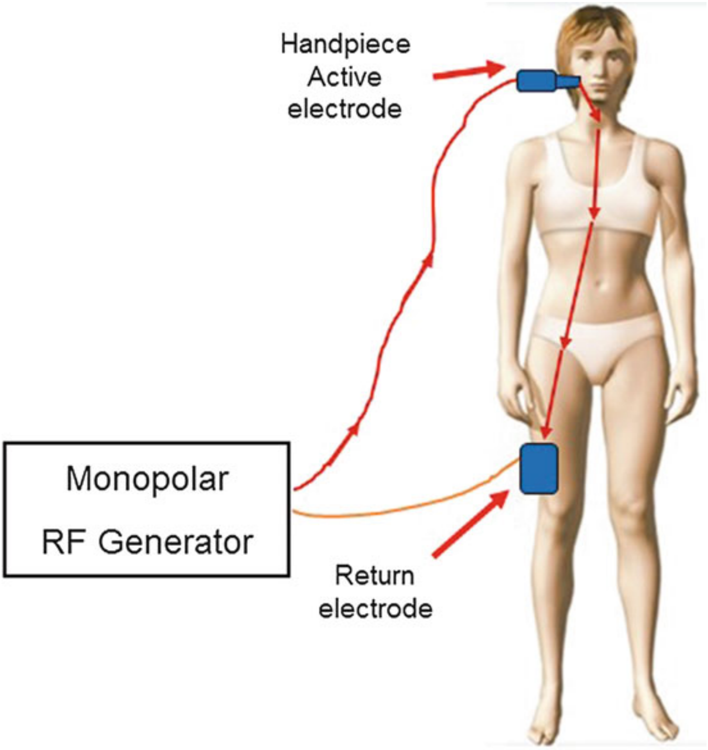

Fig. 34 Example of monopolar device used for skin tightening, Thermage ThermaCool, Solta Medical

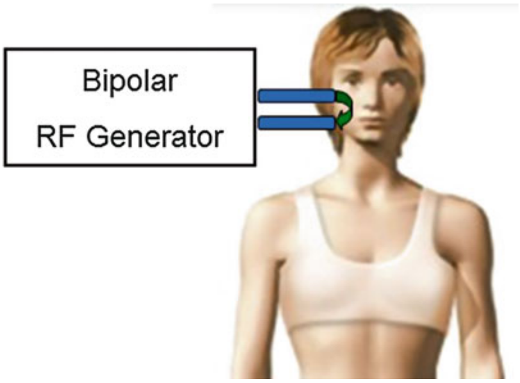

Fig. 35 Schematic of a bipolar RF system

Fig. 36 RF + suction, Reaction™ (Viora)

near the electrodes, thus allowing a greater control over the size of the treated volume.

The penetration depth is a function of the size of the electrodes and the distance between them. By increasing the separation of the electrodes, the RF current can go deeper, but the divergence also increases thus reducing the desired heating effect. If the separation is too high compared to the electrode size, the heating profile will be similar to two monopolar electrodes. When the separation of the electrodes is comparable to the size of the electrode, the penetration depth is approximately half of the distance between them (Lapidoth and Halachmi 2015).

The folding of the skin between the electrodes, for example, by applying negative pressure (in the form of vacuum), allows a uniform heating of a large tissue volume that can reach up to a few centimeters. This technique is used in devices for body contouring and cellulite such as Reaction™ of Viora (Fig. 36) and VelaShape™, which uses the electro-optical synergy (ELŌS) technology developed by Syneron Candela, described below.

Multipolar RF

It is an interesting approach to the bipolar RF geometry. In this case, a series of bipolar electrodes are used in a circular or linear configuration. The RF current flows between them, producing a more homogeneous heating effect over a larger tissue volume and variable penetration depths, as shown in Fig. 37. It also quickly reaches the desired treatment end point

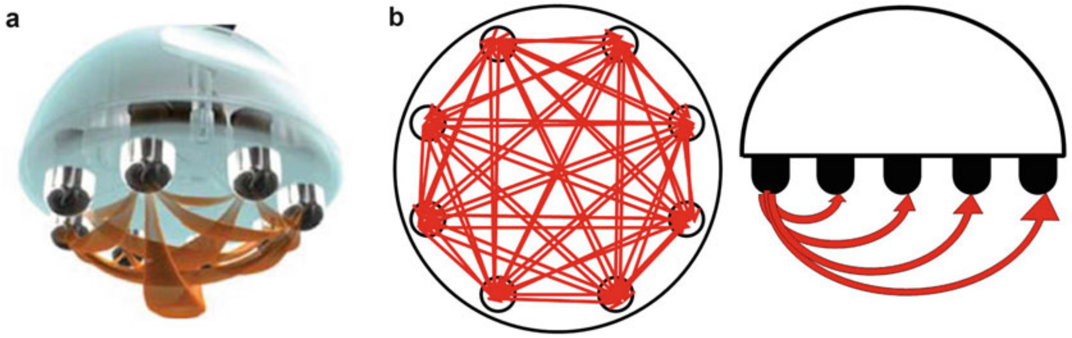

Fig. 37 (**a**) Schematics of a multipolar RF configuration showing RF current flow between electrodes (**b**) at different penetration depths

Fig. 38 Freeze™ multipolar RF and its applicators, from Venus Concept

temperature, since more electrodes are used simultaneously (Figs. 37 and 38).

Unipolar RF

This RF configuration uses a single electrode that works, in some ways, as an antenna for electromagnetic energy coupling in the skin. It is different from monopolar RF, which uses one active electrode and one return electrode, and in this case, the RF current flows into the skin (Fig. 39).

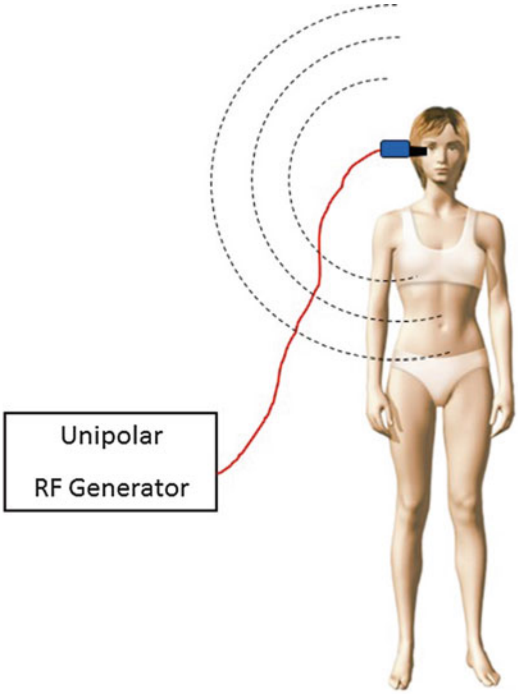

Fig. 39 Schematics of a unipolar RF generator

The electromagnetic field coupling in human tissue produces heat. The RF heating effect depends on the operating frequency of the device. There are two mechanisms of heating biological tissue containing water: ionic current, which is produced by moving charged particles (electrons), and rotation of dipoles of water molecules. These two forms of interaction lead to heating and consequent increase in temperature of the biological tissue (Lapidoth and Halachmi 2015) (Fig. 40).

Fig. 40 The platform Accent Ultra™, from Alma Lasers, with a unipolar handpiece

Fractional RF

Fractional bipolar RF (FRF) was developed following the same concepts and success of fractional lasers as described previously and is gaining great popularity in dermatology. The procedure is based on the heating or ablation of multiple small points in the skin (MTZ), with a spot size of 100–400 μm, leading to improvements in the quality of the skin, wrinkle reduction, and treatment of acne scars and stretch marks (Lapidoth and Halachmi 2015; Brightman et al. 2009; Rongsaard and Rummaneethorn 2014).

The RF has the potential to provide different patterns of energy and heat distribution from the MTZ shape interaction of fractional lasers. In contrast to lasers where the thermal effect is limited to the periphery of the ablation crater (ablative procedure) or the coagulated column (in non-ablative procedures), the RF energy flows through the entire dermis, adding volumetric heating to the fractional treatment. This produces a more effective effect of skin tightening.

There are mainly two types of RF fractional technologies:

1. A matrix of bipolar microelectrodes applying the RF energy from the surface
2. A grid of microneedles which internally deliver the RF energy within the dermis

The surface electrodes provide a more superficial effect improving texture and lines, treating stretch marks and smoothing acne scars. The bipolar RF is applied with a matrix of active microelectrodes as shown in (Fig. 41).

A normal bipolar device, described above, uses a large area electrode and has low power density, and the current and subsequent heating effect is limited to the tissue between the electrodes. In FRF, the active electrode is converted into a series of microelectrodes, which increases the energy density, thus producing an ablation effect near the electrode, and as the energy flows to the large return electrode, it spreads, reducing the effect which is limited to skin coagulation and skin tightening (Fig. 42). This action is similar to a water nozzle. If we approach the nozzle, and the water jet is concentrated, we can become excessively wet. As we move away from the nozzle, the water spreads and only a few drops can reach us (Fig. 42).

An interesting variation of the fractional bipolar RF was developed by Syneron Candela, the “Sublative RF,” used in the Matrix RF and eMatrix devices. The proposal is to deliver heat energy to the dermal layer of the skin with minimal epidermal damage. By controlling the RF current energy and delivery pulse, it is possible to correct epidermal defects and promote aggressive remodeling of the deeper dermis. Since the effect on the epidermis is minimal, the recovery time is shorter, and it also reduces the risk of infection and pigmentary changes (Fig. 43).

The RF microneedle approach is based on the introduction of a set of fine dielectric-coated needle electrodes deep into the skin, which is then activated to deliver energy producing a strong dermal remodeling. Since the energy is directly deposited into the deep dermis, there is no effect in the epidermis, which is preserved. Side effects

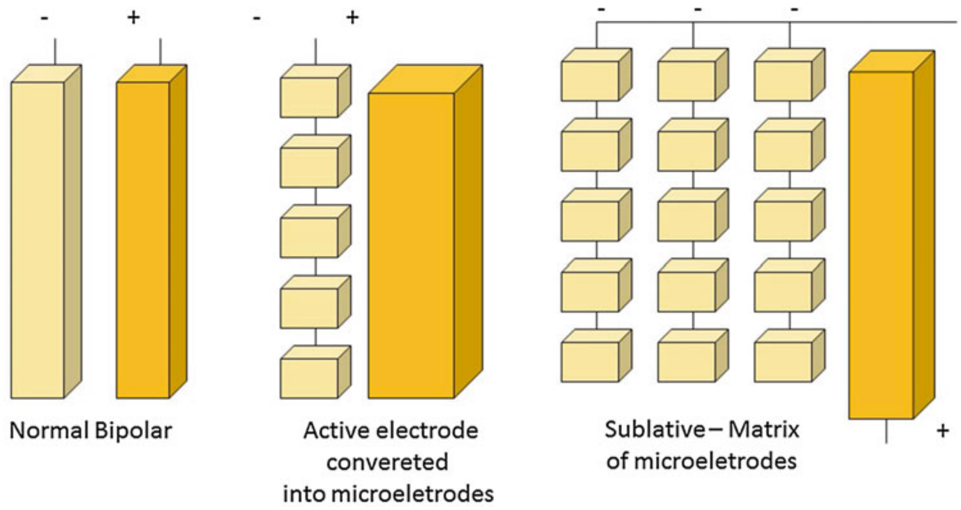

Fig. 41 Schematics of a fractional RF device

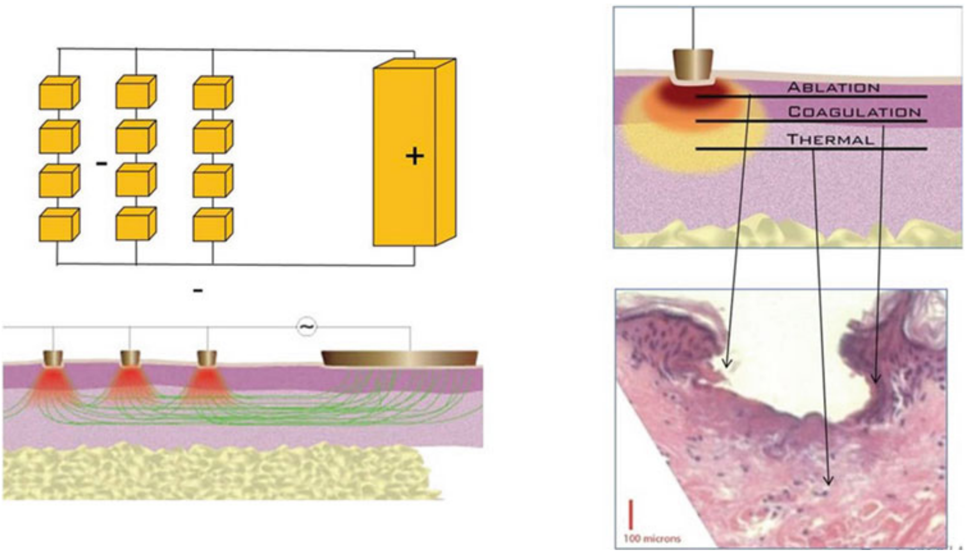

Fig. 42 Impact of the fractional RF in the tissue

and recovery time are minimal. Compared to the surface fractional RF application, microneedles can produce higher temperatures in the deep dermis and therefore stronger collagen contraction, which leads to the improvement of deep wrinkles and skin tightening (Lapidoth and Halachmi 2015).

The RF energy penetration depth is controlled by adjusting the size of the needle, and the effect is confined to the skin between the electrodes (Fig. 44).

The combination of a superficial fractional treatment (Sublative), improving epidermis and collagen remodeling in the upper dermis, with deep dermal remodeling produced by the microneedle device represents a high potential for a complete skin improvement with minimal adverse effects and recovery time.

Fig. 43 The eMatrix™ and the Sublative™ tip, from Syneron Candela

Fig. 44 INFINI™ skin treatment platform, with surface fractional RF and microneedle handpieces, from Lutronics Inc.

It is often said that fractional RF is safe for all skin types because of its “color-blind” characteristic. However, it should be noted that, while the RF interaction with skin does not depend on the presence of melanin or any other chromophore, darker skin types and tanned skin are still susceptible to post-inflammatory hyperpigmentation (PIH). The FRF will heat and induce a wound healing process response in the skin; therefore, it is wise to treat these high-risk skin types with greater caution.

Hybrid Systems

Looking to overcome limitations and to expand the safety and efficacy of treatments with laser or intense pulsed light (IPL) systems, the industry has diversified technology associating light to other forms of energy creating the so-called hybrid systems.

An example of great success of this diversification is the electro-optical synergy (ELŌS™) technology synergy of light with radio frequency (RF) developed by the inventor of the intense pulsed light, Dr. Shimon Eckhouse, in Syneron Candela, Israel (Doshi and Alster 2005; Sadick et al. 2005; Lapidoth et al. 2005; Sadick and Trelles 2005).

The ELŌS™ technology employs a bipolar RF with a water-cooled tip simultaneously with the laser or IPL pulse, as illustrated in Fig. 45.

Following the principle of selective photothermolysis, light heats the chromophore preserving the surrounding tissue. A cool tip protects the surface of the skin and “pushes” the RF to deeper

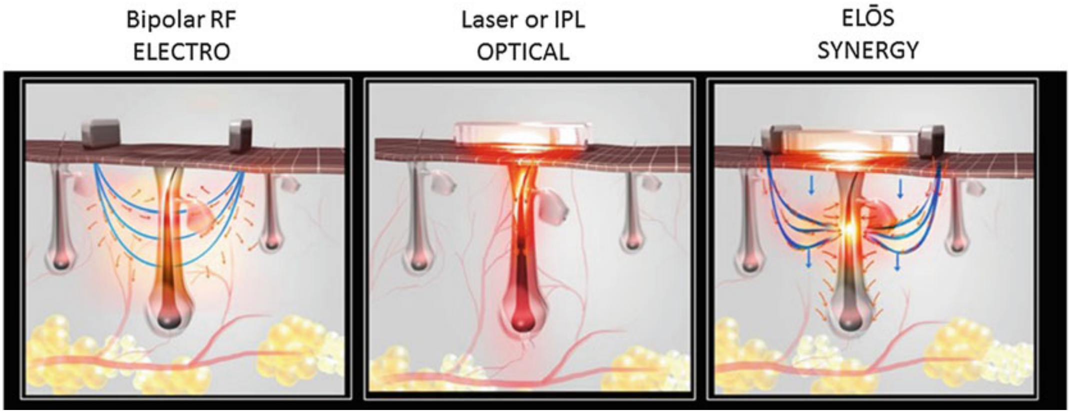

Fig. 45 The ELŌS™ effect, synergy of bipolar RF + light in hair removal

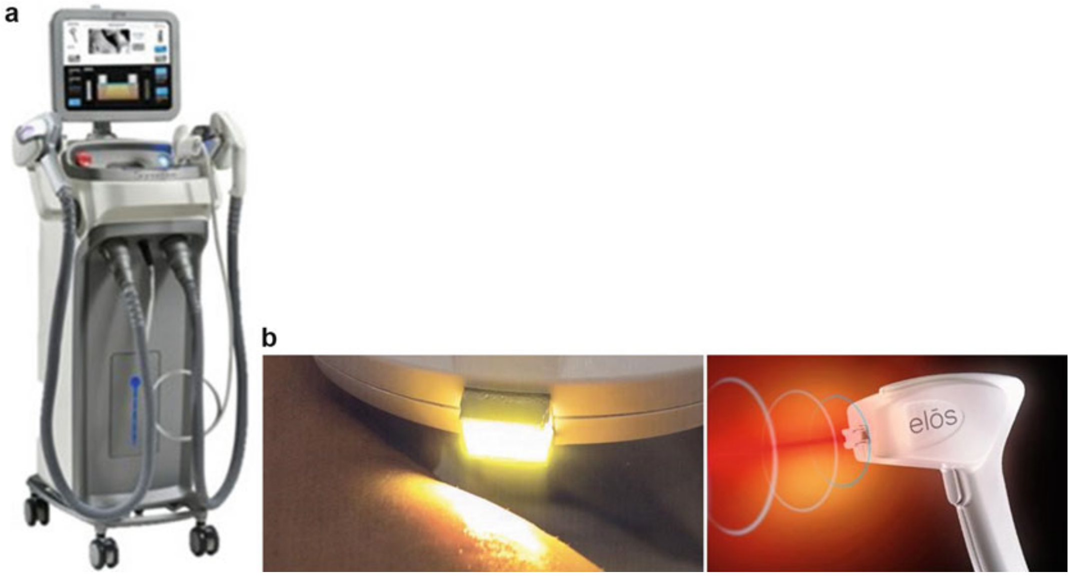

Fig. 46 (**a**) ELŌS plus system, Syneron Candela – multi-platform with several handpieces including laser, IPL, and infrared, all associated with bipolar RF, and a fractional RF. (**b**) ELŌS handpiece showing the bipolar electrodes and the IPL simultaneously

layers. The RF will be concentrated in the heated tissue because it has better conductivity, and this will cause the chromophore to overheat leading to the desired therapeutic effect (Lapidoth and Halachmi 2015).

Figure 45 illustrates this synergic effect in hair removal treatment, but the same occurs in the treatment of pigmented and vascular lesions, skin rejuvenation, and tightening (in which an infrared light source in the range from 700 to 1200 nm is used with bipolar RF) (Figs 46a, b).

The main advantage of the ELŌS™ is the reduced optical fluence needed for the treatment, thus minimizing patient discomfort during the session and increasing safety for darker skin types. Because of the RF action, simultaneous effects such as skin tightening during a treatment of pigmented lesions can also happen.

Fig. 47 ELŌS for circumferential and fat reduction, cellulite treatment, and skin tightening, VelaShape III (Courtesy: Syneron Candela)

Other applications of this technology are circumferential reduction, cellulite treatment, and skin tightening. In this case, bipolar RF is associated with an infrared source, a lamp emitting from 700 to 2,000 nm, or a high-power LED (870 nm), rotating cylinders, which produces massage, drainage, and suction. The cylindrical rollers are the RF electrodes. The suction causes a skinfold, which increases the penetration of the RF and light as explained before (Alster and Tanzi 2005; Wanitphakdeedecha and Manuskiatti 2006; Boechat 2009) (Fig. 47).

The goal is to increase the temperature of (up to 43 °C) deep tissue, which accelerates the metabolism of fat cells and thereby reduces their size leading to circumferential reduction. For a longer exposure time and higher temperature (45 °C), it is possible to produce apoptosis of fat cells since they are more sensitive than skin cells thus reducing localized fat. The effect of skin tightening occurs because of the stretching of elastic fibers and the remodeling of collagen, improving the overall skin quality.

Applications of Laser in Dermatology

Laser for Vascular Lesions

Vascular lesions have been some of the most frequently treated skin conditions since the advent of lasers. The flash-lamp-pumped pulsed dye laser (PDL) has a wavelength between 585 and 600 nm and is used to treat superficial blood vessels, as these wavelengths coincide with the absorption peaks of oxyhemoglobin (Anderson and Parrish 1983; Spicer and Goldberg 1996). Vascular-specific laser systems target intravascular oxyhemoglobin leading to the destruction of various congenital and acquired vascular lesions. Three main absorption peaks for oxyhemoglobin are within the visible range of the electromagnetic spectrum: 418, 542, and 577 nm. Lasers that have been used to treat vascular lesions include the argon (488–514 nm), argon-dye laser (577 and 585 nm), KTP (532 nm), krypton (568 nm), copper vapor/bromide (578 nm), PDL (585–595 nm), and Nd:YAG (532 and 1,064 nm) (Anderson and Parrish 1983; Spicer and Goldberg 1996; Osorio and Torezan 2009; Tanzi et al. 2003a). At 577 nm, the PDL penetrates the skin to a depth of 0.5 mm, 0.2 mm below the dermoepidermal junction, for treatment of dermal vascular lesions. Penetration can be further increased to 1.2 mm if the wavelength is changed to 585 nm. At this longer wavelength, less light is absorbed by melanin. Therefore, the risks of depigmentation are decreased (Tanzi et al. 2003a).

Purpura-inducing effect of the PDL in the treatment of capillary malformations is one of the most common side effects observed (Dover et al. 1995). In general, the smaller the pulse duration, the more explosively energy is delivered and the more likely it is to induce purpura. The classic short pulse duration (0.45–1.5 ms) that ruptures small vessels is still the most effective pulse duration for treating capillary malformations, with the expected purpura as a clinical end point. With a pulse duration (450 μs) shorter than the thermal relaxation time (TRT) of small- to medium-sized blood vessels (1 ms), the PDL respects the principles of selective photothermolysis leading to selective vascular injury avoiding thermal damage to the surrounding tissue. On the other hand, longer pulse durations coagulate the blood vessels and do not induce purpura (Anderson and Parrish 1983; Tanzi et al. 2003a; Dover et al. 1995). Diffuse erythema of the face and more superficial telangiectases may benefit from the sub-purpuric parameters. Due to the low-risk profile, PDL has been used to treat a variety of vascular lesions such as port-wine stains, facial telangiectases, hemangiomas, pyogenic granulomas, Kaposi's sarcoma, and poikiloderma of Civatte (Tanzi et al. 2003a; Dover et al. 1995; Tan et al. 1989; Reyes and Geronemus 1990; Ashinoff and Geronemus 1991; Alster and Wilson 1994; Fitzpatrick et al. 1994; Kauvar and Geronemus 1995).

The Nd:YAG laser has a wavelength of 1,064 nm, which can also be used in the treatment of vascular lesions. This longer wavelength corresponds to the optical window that enables deeper penetration into the dermis to target larger vessels and is less likely to produce bleeding. However, it is important to emphasize that at 1,064 nm, there is more penetration into the skin but less absorption by hemoglobin. Therefore, melanin and water may act as competing chromophores (Osorio and Torezan 2009; Tanzi et al. 2003a; Stewart et al. 2013). High-energy settings or absence of a cooling device can cause bulk heating, resulting in burns and scarring. Generally, 1,064 nm Nd:YAG laser is used to treat larger vessels, such as larger capillaries malformations and venules of the face and limbs, as well as bluish vascular lesions such as venous lakes. The double-frequency Nd:YAG laser – KTP laser – (by halving the 1,064–532 nm when the beam passes through a KTP crystal) is currently used to treat very superficial facial telangiectases as it closely matches one of the most superficial hemoglobin absorption peaks (Tanzi et al. 2003a; Stewart et al. 2013). Compared with longer wavelength vascular-specific lasers, potential limitations of the 532-nm wavelength include decreased tissue penetration of its shorter wavelength resulting in diminished absorption by deeper vessels. In addition, the 532-nm wavelength is more absorbed by melanin than PDL, which may limit its use for patients with darker skin types.

The other abovementioned krypton, argon, argon-dye, copper vapor/bromide, and some KTP devices are continuous or semicontinuous (quasi-CW) lasers that are used to treat cutaneous vascular conditions such as rosacea, poikiloderma of Civatte, and port-wine stains. These devices are not pulsed systems and consequently they offer higher risks of thermal damage to the surrounding skin. Thus, using continuous or quasi-CW lasers is often associated with higher incidences of hypertrophic scarring and textural changes than is seen with pulsed laser systems (Tanzi et al. 2003a; Stewart et al. 2013; Apfelberg 1980).

Laser for Pigmented Lesions

The major endogenous pigment of clinical importance is melanin, whereas tattoo ink (amateur, professional, iatrogenic, or traumatic) is the most commonly targeted exogenous pigment. Melanin does not have any especific absorption peak. However, it increasingly absorbs shorter wavelengths of light below about 1,000 nm. Therefore, a multitude of laser wavelengths can be used to target melanin, although none is entirely specific for this chromophore: 532 nm Nd:YAG KTP, 595 nm PDL, 694 nm ruby, 755 nm alexandrite, and 10,640 nm Nd:YAG (Anderson and Parrish 1983; Osorio and Torezan 2009; Goldberg 1993).

Melanin-specific, high-energy, QS laser systems can successfully lighten or eradicate a variety of benign epidermal and dermal pigmented lesions and tattoos with minimal risk of untoward effects. Epidermal lesions (solar lentigines, ephelides, cafe'-au-lait macules, and seborrheic keratoses), dermal and mixed epidermal/dermal lesions (melanocytic nevi, blue nevi, nevi of Ota/Ito, infraorbital hyperpigmentation, Becker's nevi, and nevus spilus), and tattoo pigment area all are suitable to QS laser treatment (Chang et al. 1996; Shimbashi et al. 1997; Yang et al. 1996; Ono and Tateshita 1998; Osorio and Torezan 2009; Tanzi et al. 2003a; Stewart et al. 2013; Grevelink et al. 1997b; Ueda and Imayama 1997; Kunachak et al. 1999; Alster and Williams 1995). Melasma, which is considered one of the most difficult-to-treat skin diseases, may benefit from QS lasers at very low fluences and high repetition rates, targeting the melanosome with minimal surrounding inflammatory process. In this case, many treatment sessions performed weekly are necessary to achieve the best results, although not long-lasting in the authors' experience (Jeong et al. 2008; Mun et al. 2010).

Based on Anderson and Parrish's principle of selective photothermolysis, QS laser systems replaced earlier CW lasers as a result of their ability to induce thermal necrosis that remains largely confined to the melanosomes with limited spread of coagulative necrosis to surrounding structures (Anderson and Parrish 1983; Rongsaard and Rummaneethorn 2014). Before the QS lasers' advent, the continuous and quasi-CW laser systems have been used for pigment and tattoo destruction. These lasers typically emit light with pulse durations longer than the thermal relaxation time of a melanosome and, therefore, may result in scarring or textural irregularities as a result of excessive thermal damage of surrounding tissue during laser irradiation. Therefore, the use of CW lasers is reserved for removal of epidermal lesions because treatment of deeper, dermal lesions is often associated with significant tissue scarring (Osorio and Torezan 2009; Tanzi et al. 2003a; Stewart et al. 2013).

The QS laser produces high-energy nanosecond pulses in the green to near-infrared spectrum that selectively target melanin or ink and are less likely to cause adverse effects (Raulin et al. 1998). The wavelengths of the Q-switched ruby (694 nm), alexandrite (755 nm), and double-frequency Nd:YAG (532 nm) lasers are the most commonly used. The QS 1,064 Nd:YAG laser penetrates deeper into the skin, becoming suitable for the treatment of deeper pigmented lesions and darker-skinned individuals (Raulin et al. 1998; Tanzi et al. 2003a; Stewart et al. 2013; Apfelberg 1980; Goldberg 1993; Ashinoff and Geronemus 1992).

Superficial pigment is best treated with short wavelength lasers, whereas deeper pigment responds better to long wavelengths with a greater penetration. Dark-skinned patients are more safely treated with long-wavelength lasers, preventing the superficial uptake of laser energy by epidermal melanosomes and thus reducing the potential depigmentation (Osorio and Torezan 2009; Tanzi et al. 2003a).

With the development of QS laser technology, tattoo removal has become much safer (Osorio and Torezan 2009; Tanzi et al. 2003a; Goldberg 1993; Ashinoff and Geronemus 1992; Kilmer and Garden 2000; Haedersdal et al. 1996). For optimal pigment removal, the choice of laser is based on the absorption spectra of the ink colors present within the tattoo. Black pigments absorb throughout the red and infrared spectrum and can be treated with QS ruby (694 nm), QS alexandrite (755 nm), or QS Nd:YAG (1,064 nm) lasers. Blue and green inks are targeted in the 600- to 800-nm range, thus making the ruby or alexandrite laser the most appropriate choice. Red, orange, and yellow tattoo inks are specifically destroyed by green light, rendering the 532-nm QS Nd:YAG laser or 510-nm PDL the optimal treatment for these colors. It is important to emphasize that QS lasers may also be used as long-pulse lasers, in the millisecond pulse domain width (Kilmer and Garden 2000; Haedersdal et al. 1996; Reid et al. 1983; Taylor et al. 1990; Kilmer and Anderson 1993; Fitzpatrick et al. 1993). Therefore, in the long-pulse mode, they cannot adequately and safely target small-diameter melanosomes or ink particles. Competing chromophores within skin structures, such as capillaries, present greater relevance with long-pulse-width lasers. Long-pulse lasers can target larger structures such as clusters of lentiginous melanocytes or pigmented hair shafts and can be useful for hair removal (Campos et al. 2000; Eremia et al. 2001; Dierickx et al. 1998; Grossman et al. 1996).

The most common side effects are punctate bleeding, edema, pruritus, vesiculation and blistering, purpura, hypopigmentation or hyperpigmentation, scarring, permanent hair loss, and systemic allergic or localized granulomatous reactions to disrupted tattoo ink particles. Some of these side effects are more prone in dark-skinned individuals due to the increased absorption by surrounding melanin (Tanzi et al. 2003a; Stewart et al. 2013).

Recently, the development of new QS lasers 755 nm and 1,064 nm which operate in picosecond domain resulted in more specific damage confined to the tattoo particle. Optimal selective photothermolysis of a pigment particle requires pulse durations equal to or less than the particle's thermal relaxation time. Since tattoo particles in skin range in diameter from 40 to 300 nm, picosecond pulses would approximate TRT more closely and, therefore, might be more effective at tattoo particle fragmentation (Freedman et al. 2014; Ibrahimi et al. 2013).

Resurfacing: Ablative Technology

Cutaneous laser resurfacing represents a major advance in the treatment of photodamaged facial skin and atrophic scarring. With recent advances in laser technology, especially with the advent of fractional ablative systems, this procedure has become widely accepted as an effective means for facial rejuvenation (Stewart et al. 2013).

Ablative lasers are generally used to resurface and rejuvenate the skin by treating rhytides and scars. The first continuous carbon dioxide laser emits a beam of far-infrared radiation at 10,600 nm, mainly targeting water. The CW-CO_2 laser does not conform to the principle of selective photothermolysis and thus induces more depigmentation and scarring (Rongsaard and Rummaneethorn 2014; Waldorf et al. 1995; Alster and Garg 1996). However, this technology is still used as a relatively bloodless skin incision tool, but for resurfacing purposes has given way to high-energy and pulsed CO_2 laser. These newer systems are able to effect controlled tissue ablation with limited coagulative necrosis of unintended neighboring structures. Because of its flexibility and low side-effect profile, the high-energy, pulsed, and scanned CO_2 laser has been considered the gold standard for facial rejuvenation (Waldorf et al. 1995; Alster and Garg 1996; Fitzpatrick et al. 1996; Apfelberg 1997; Ross et al. 1999a; Dover et al. 2000). Ablation is defined as rapid cellular heating and instant tissue vaporization and can remove 20–60 mm of the skin surface after a single pass. Additionally to the ablated layer, a zone of collateral thermal damage (200 to 300-μm) occurs as a consequence of heat diffusion (Ross et al. 1999a; Dover et al. 2000). The tissue coagulation and protein denaturation lead to hemostasis and collagen remodeling. The latter may take up to several months to achieve its maximal effect, but the resulting improvement in rhytides and scarring is significant (Tanzi et al. 2003a; Fitzpatrick et al. 1996; Apfelberg 1997; Ross et al. 1999a; Dover et al. 2000; Fitzpatrick 2002). Besides the excellent final outcome for skin rejuvenation, the incidence of side effects was considered potentially high, including infection, pain, prolonged erythema, milia, scarring, permanent late hypopigmentation, and demarcation lines between treated and non-treated skin (Fitzpatrick 2002; Alam and Warycha 2011).

The short-pulsed 2,940-nm Er:YAG laser was developed subsequent to the CO_2 laser in an attempt to emulate some of its beneficial effects while limiting its side-effect profile and morbidity (Stewart et al. 2013; Goldman et al. 1999). The Er:YAG laser has a higher absorption coefficient than that of the CO_2 laser. Because 90% of the epidermis is composed of water, most of the energy of the erbium laser is superficially absorbed. The erbium laser can, therefore, effect fine tissue ablation, penetrating to an average depth of 2–5 μm per J/cm^2 with zones of thermal necrosis extending another 10–15 μm. Collateral thermal damage is reduced and minimal vascular coagulation is effected, leading to inefficient hemostasis during treatment (Osorio and Torezan 2009; Tanzi et al. 2003a). The limited thermal damage also accounts for the less pronounced clinical improvement typically seen after with CO_2 laser. Another ablative wavelength, 2,790 nm, gave rise to the erbium-doped yttrium scandium gallium garnet laser (YSGG) (Er:YSGG) (Stewart et al. 2013). Besides the improvement of skin aging, other well-known indications of ablative lasers are removal of benign epidermal and dermal lesions such as seborrheic keratoses, verruca vulgaris, xanthelasma, and sebaceous gland hyperplasia and adnexal tumors such as syringoma and trichoepithelioma; treatment of premalignant and malignant skin lesions, including actinic cheilitis, superficial basal cell carcinoma, and squamous cell carcinoma in situ has been reported (Spicer and Goldberg 1996; Osorio and Torezan 2009; Tanzi et al. 2003a; Stewart et al. 2013). The CO_2 laser can also be used for excisional and incisional operations, including blepharoplasty or rhytidectomy, with the advantage of the near-bloodless field created from the CO_2 laser-tissue interaction, effecting minimal postoperative edema or bleeding (Ross et al. 1999a; Dover et al. 2000; Fitzpatrick 2002).

Resurfacing: Non-ablative Technology

Non-ablative resurfacing lasers preserve the epidermis either relatively or absolutely while still allowing bulk heating and denaturation of the dermal proteins. As a consequence, they allow for the beneficial effects of tissue remodeling and skin tightening with decreased recovery time and lower risk of scarring, depigmentation, and infection (Tanzi et al. 2003a; Bjerring et al. 2000).

Non-ablative laser used today emits light within the infrared portion of the electromagnetic spectrum (1,000–1,600 nm), along with other modalities such as RF, focused ultrasound, and IPL, which have all been used as non-ablative resurfacing therapies (Stewart et al. 2013; Alexiades-Armenakas et al. 2008; Zelickson et al. 1999). Specific lasers for dermal targets such as hemoglobin and deeper melanin are non-ablative lasers, but in current nomenclature, non-ablative lasers are those that target dermal water while preserving the same target, water, in the epidermis. At these wavelengths (1,000–1,600 nm), absorption by superficial water-containing tissue is relatively weak, thereby effecting deeper tissue penetration. Non-ablative laser resurfacing induces collagen remodeling by creation of a dermal wound without damaging the epidermis (Tanzi et al. 2003a; Levy et al. 2001, 2002; Trelles et al. 2001; Goldberg and Metzler 1999; Goldberg and Whitworth 1997b; Rostan et al. 2001; Tanzi et al. 2003b). Contact and dynamic cooling devices are used simultaneously with laser irradiation to ensure epidermal preservation. The classical non-ablative lasers are not capable of results comparable with those of ablative laser systems and have shown to improve mild to moderate atrophic scars and rhytides with virtually no external wound. Non-ablative laser resurfacing is ideal for patients with either mild cutaneous photoaging (Alexiades-Armenakas et al. 2008; Zelickson et al. 1999; Levy et al. 2001, 2002; Trelles et al. 2001; Goldberg and Metzler 1999; Goldberg and Whitworth 1997b; Rostan et al. 2001; Tanzi et al. 2003b). In addition, the results may differ between individuals, multiple treatments are necessary, and maintenance with repeat treatments is required. In practice, the results achieved with these laser devices are far from being reasonable, and they are no longer routinely offered to patients (Waldorf et al. 1995; Tanzi et al. 2003b; Levy et al. 2002).

Fractionated Lasers

The introduction of fractionated lasers in 2004, by Manstein et al., represented the beginning of a new era in the application of laser technologies in dermatology. Initially, the fractionated systems covered the non-ablative wavelengths, specifically 1,550 nm (Manstein et al. 2004). These devices rely on high-fluence irradiation to form multiple, discrete vertical zones of thermal damage with completely spared intervening areas. These microthermal zones (MTZ) may vary in depth and width depending on the levels of energy and density set. The MTZ are separated by uninvolved tissue (accounting for up to 75–85% of the treated surface area), which act as a reservoir for tissue regeneration by providing nutritional support and an intact microstructure for keratinocyte and fibroblast migration (Manstein et al. 2004; Manstein and Laubach 2011).

Fractionated lasers can be either non-ablative or ablative. In general, the fractional ablative devices are more effective but tend to have longer recovery time than the fractional non-ablative devices. Non-ablative devices (Nd:YAG, Er: glass, Er:fiber, and Er:thulium) have wavelengths of between 1,320 and 1,927 nm, while the ablatives (Er:YAG, Er:YSGG, and CO_2) have longer wavelengths between 2,940 and 10,600 nm (Manstein et al. 2004; Geronemus 2006; Manstein and Laubach 2011).

The most widely known and extensively evaluated fractionated laser, the 1,550 nm Er:glass, typically produces erythema and edema lasting 2–3 days post-procedure. However, this non-ablative laser usually requires multiple sessions and may only show modest improvements in rhytides and skin tightening when compared with the ablative CO_2 (Manstein et al. 2004; Manstein and Laubach 2011). Besides this, fractional non-ablative lasers provide good results for photoaging, acne scars, and stretch marks, with little downtime and relatively safe profile. The side effect profile of these lasers was greatly improved, with pinpoint bleeding generally lasting less than 24 h and moderate erythema lasting only 1 week. However, high-setting parameters of these lasers can produce prolonged erythema and more complications such as scars, ulceration, and depigmentation (Stewart et al. 2013; Ramsdaell 2012).

The non-ablative fractionated devices progressed to ablative fractionated versions of Erb: YAG 2,940 nm and CO_2 10,600 nm to produce results approaching those seen with the non-fractional ablative CO_2 laser. Considering their high efficacy and lower incidence of side effects (compared to the non-fractional ablative lasers), these systems are now considered by many to be the gold standard in skin resurfacing (Manstein and Laubach 2011; Tierney et al. 2012).

Photoepilation

Lasers and IPL sources with wavelengths in the red or near-infrared region (600–1,200 nm) are most often used for hair removal because they effectively target melanin within the hair shaft, hair follicle epithelium, and heavily pigmented matrix (Campos et al. 2000; Eremia et al. 2001; Dierickx et al. 1998; Grossman et al. 1996). Furthermore, devices operating within this region of the electromagnetic spectrum can penetrate to the appropriate depth of the dermis because they are within an "optical window" in which selective absorption by melanin is coupled with deep penetration of laser energy (Campos et al. 2000). However, the presence of melanin within the epidermis represents a competing site for laser energy absorption. Therefore, active cooling must be used to minimize epidermal injury, especially in darker skin types (Lasers Surg et al. 1997; Nanni and Alster 1998).

Laser-tissue interactions that occur within the melanin-rich matrix and hair shaft heat the surrounding follicle. To limit the thermal damage, the pulse duration should be shorter or equal to the thermal relaxation time of the hair follicle estimated to be approximately 10–100 ms, depending on the diameter of the follicle (Lasers Surg et al. 1997; Nanni and Alster 1998; Ross et al. 1999b; Dierickx 2002). Thus, most systems currently used for long-term hair reduction provide pulse durations in the millisecond domain. However, other components of the follicular unit, such as follicular stem cells, do not contain significant amounts of melanin and may be located some distance from the targeted pigmented structures.

Laser systems and IPL sources currently used for the reduction of hair include the long-pulse (LP) ruby (694 nm), LP alexandrite (755 nm), pulsed diode (800 nm), QS and LP Nd:YAG (1,064 nm) lasers, and IPL (590–1,200 nm) sources (Nanni and Alster 1998; Ross et al. 1999b; Dierickx 2002; Gold et al. 1997). The longer the wavelength, the higher the penetration into the skin and the safer it becomes for dark-skinned individuals. So for dark skin types, it is preferable to use a 800 or 1,064 nm laser system instead of a 694 nm, which will be also absorbed by the epidermal melanin, thus leading to more depigmentation (Campos et al. 2000; Dierickx et al. 1998; Nanni and Alster 1998).

Other components of the follicular unit, such as follicular stem cells, do not contain significant amounts of melanin and may be located some distance from the targeted pigmented structures. Recently, it has been proposed that pulse durations longer than the TRT of the shaft may be more appropriate to induce permanent hair reduction. In contrast to the original theory of selective photothermolysis, the extended theory proposes that the target be destroyed by heat diffusion from the pigmented area to the target rather than by direct heating. Preliminary studies demonstrate superpulse heating of the follicle with a pulse duration longer than 100 ms has resulted in long-term hair reduction without adverse sequelae (Stewart et al. 2013; Ross et al. 1999b).

Side effects are rare and may include blistering, fine epidermal crusting, purpura, and transient hyperpigmentation or hypopigmentation. Patients at highest risk of complications are those with recent sun exposure or darker skin types (Campos et al. 2000; Dierickx et al. 1998; Alam and Warycha 2011).

IPL sources emitting wavelengths ranging from 550 to 1,200 nm can also be used to effect hair reduction. By using a series of cutoff filters, a specific wavelength may be selected to suit an individual skin type and color. As well as with lasers, IPL requires multiple treatment sessions to result in a considerable hair reduction. Side effects and complications of IPL treatment are similar to those seen after laser-assisted hair removal and include rare instances of blistering, crusting, and transient depigmentation (Dierickx 2002; Gold et al. 1997).

Intense Pulsed Light Systems

As with lasers, IPL devices have been used to treat vascular lesions, dyschromia, unwanted hair, acne, and sebaceous hyperplasia. Cutoff filters allow the emission of longer wavelengths, which reduce relative absorption by melanin, protecting darker skin types and relatively increasing nonspecific absorption by water (Weiss et al. 2011). IPL is primarily indicated for targeting melanin and hemoglobin and works best for treating colored chromophores rather than texture. Appropriate filters (560–590 nm) selectively emit light that correspond to the absorption peaks of hemoglobin, thus targeting vascular structures in a manner analogous to the theory of selective photothermolysis (Babilas et al. 2010).

It has been used to successfully treat a variety of vascular lesions including facial telangiectases, port-wine stains, and hemangiomas (Osorio and Torezan 2009; Tanzi et al. 2003a; Weiss et al. 2011). Filters are used to eliminate shorter wavelengths, thereby concentrating light energy so that improved dermal penetration is achieved. Light is delivered as a series of pulse sequences with pulse durations of 2–25 ms and delays between pulses ranging from 10 to 500 ms (Babilas et al. 2010). Because shorter-wavelength light interacts more readily with epidermal melanin, the lower cutoff filters should only be used in patients with fair skin types. With longer pulse durations, the IPL source can slowly heat more deeply located vessels, thus improving treatment efficacy and decreasing the risk of postoperative purpura and hyperpigmentation, but caution is necessary to avoid such side effects. Larger caliber vessels respond well to these treatments because high-energy densities can be delivered by trains of pulses with relatively long delays (40–60 ms) between each pulse (Tanzi et al. 2003a; Stewart et al. 2013). IPL sources emitting wavelengths ranging from 550 to 1,200 nm can also be used to effect hair reduction. By using a series of cutoff filters, a specific wavelength may be selected to suit an individual skin type and color (Dierickx 2002; Gold et al. 1997).

Adverse effects may include purpura, swelling, blistering, inappropriate photoepilation, burns or scarring (darker skin types or sun-tanned skin), demarcation lines, and depigmentation.

Radio Frequency

RF treatments are an alternative to lasers and can be used as monotherapy or as adjuvant therapy with fractional lasers. Three major types of RF treatments exist: unipolar, bipolar, and fractional (Stewart et al. 2013). The most basic is the unipolar/monopolar RF device that uses a single electrode and a grounding pad on the skin. This RF modality offers deeper penetration of the dermis but increased pain and discomfort to the patient. Bipolar RF offers an alternative to unipolar/monopolar RF that can deliver a more focused current to the dermis with less pain due to the need to use lower amounts of energy. Fractional RF uses an array of electrodes that allows for zones of thermal wounds to be made between areas of unaffected zones, thus stimulating dermal remodeling and allowing for a supply of reservoir cells to promote healing (Brightman et al. 2009). Variations of fractional RF employ microneedles to deliver electrical current to a particular depth within the dermis that decreases damage to the epidermis. Furthermore, there are alternative modalities such as electro-optical synergy systems that combine RF and lasers. The pretreatment with a non-ablative laser lowers the tissue impedance (resistance to flow of current) in the skin to allow deeper penetration of the RFs, decreased level of pain, and reduced amount of RF energy to reach the optimal thermal dose, thus decreasing side effects to the surrounding dermis (Brightman et al. 2009).

The use of RF devices is based on the Ohm's law (Boechat 2009). When volumetric heat of the dermis and subdermal tissue occurs after electrical field interaction with the tissue's natural electrical resistance, the final result is collagen contraction and remodeling, leading to the desired clinical end point of skin tightening. Increased localized blood flow and improved lipolysis are thought to account for the beneficial effects seen in the treatment of cellulite, as least in theory. The epidermis is spared from thermal damage by contact cooling. The main indications of RF are skin laxity, acne scars, and photoaging skin (Osorio and Torezan 2009; Stewart et al. 2013).

The procedure produces significant discomfort and is time-consuming, and the results were somewhat unimpressive and inconsistent in the past. However, advances in handpiece design together with the use of bipolar (or multipolar) RF appears to have increased efficacy, while multiple passes at lower settings have increased patients' tolerance (Boechat 2009). Side effects are low, with transient erythema and edema commonly occurring. Blistering, scarring, and contour changes may be observed after aggressive treatments. Overall, the efficacy of this non-ablative technique remains modest when used as a monotherapy. RF can be used in combination with other modalities such as IPL and laser to produce more significant clinical improvements (Stewart et al. 2013).

Focused Ultrasound

First approved for eyebrow lifting in 2009, high-intensity focused ultrasound (HIFU) has subsequently been trialed in other body regions for the treatment of skin and tissue laxity. Ultrasonic energy is used to achieve precise micro-coagulation zones (coagulative necrosis) deep in the dermis, subcutaneous tissue, and superficial aponeurotic system (Laubach et al. 2008). In HIFU therapy, ultrasound beams are focused on the tissue, and due to the significant energy deposition at the focus, temperature within the tissue can rise to levels from 65 to 85 °C, destroying the diseased tissue by coagulation necrosis. Higher temperature levels are typically avoided to prevent boiling of liquids inside the tissue. Each sonication of the beams theoretically treats a precisely defined portion of the targeted tissue, although in practice cold spots (caused by, among other things, blood perfusion in the tissue), beam distortion, and beam mis-registration are impediments to finely controlled treatments. Tissue damage occurs as a function of both the temperature to which the tissue is heated and how long the tissue is exposed to this heat level in a metric referred to as "thermal dose" (Laubach et al. 2008; Weiss 2012). At high enough acoustic intensities, cavitation can occur. Microbubbles produced in the field oscillate and grow and can eventually implode. During inertial cavitation, very high temperatures inside the bubbles occur, and the collapse is associated with a shock wave that can mechanically damage tissue. HIFU can be used for body contouring (so-called noninvasive liposuction) and skin laxity or applied even in treatment of cancer to destroy solid tumors of the bone, brain, breast, liver, pancreas, rectum, kidney, testes, and prostate (Laubach et al. 2008; Weiss 2012; Solish et al. 2012).

Following treatment, repair of the deep tissue damage leads to contraction and tissue remodeling, resulting in the desired aesthetic effect of reduced skin laxity. The superficial dermis and collateral tissues are spared, which not only limits scarring and downtime but potentially permits HIFU to be used in darker skin types (Laubach et al. 2008; Weiss 2012). However, as with the use of RF, interindividual variation in response to HIFU treatment is significant.

Conclusion

Laser and intense pulsed light systems are pure light sources with important properties, which allow us to treat accurately and selectively different types of tissue damage, preserving the surrounding healthy tissue. Synergy with radio frequency shows how this equipment can still evolve becoming safer and more efficient. With the advent of fractional skin treatment, a new horizon of applications that are at the same time gentle and effective have emerged in dermatology.

In many applications, light appears as the only effective solution, as in the case of flat vascular lesions in the face or port-wine stains. It has brought a rapid and long-lasting result for unwanted hair removal, the treatment of pigmented lesions, and tattoo removal. It is used in skin tightening, cellulite treatment, circumferential reduction, and localized fat reduction. In a number of applications in dermatology, light emerges as an important complement to the existing techniques, as is the case of rhytidectomy in plastic surgery. It also improves body areas that normally are not treated by surgery, such as the neck, chest, hands, and arms using ablative or non-ablative fractional lasers.

The future will certainly bring more efficient and compact devices. We will have a wider range of applications and, among them, the development of lasers that have the ability to act at the cellular level, stimulating the production of enzymes, which have the purpose of preventing skin aging and skin cancer. Systems that have the subdermal fat as chromophore can open a new horizon of applications for circumferential reduction, cellulite treatment, and improved skin quality. The diagnostic medicine will also benefit from this development.

The more we study about the effects of the interaction of light with living tissue, the more we learn on how to appreciate the variety and complexity of these critical interactions. The result will certainly open doors to a large number of remarkable applications in the following years.

We only have to "tune in" with the energy of light!

Take-Home Messages

1. Laser light is by definition monochromatic, coherent, collimated, and high power, while IPL systems are polychromatic and incoherent.
2. Selective photothermolysis combines pulse duration, wavelength, and fluence to obtain the desired effect on the target, preserving adjacent tissue.
3. Superficial benign pigmented lesions can be treated with Q-switched lasers alexandrite, ruby, or double-frequency Nd:YAG, but also IPL devices can be employed.
4. Fractionated lasers use very high-fluence irradiation to form multiple discrete vertical zones of thermal damage sparing tissue between them. This allows a faster healing time of the treated area.

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