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Laser History, Physics, and Safety

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Abstract

Electromagnetic radiation from various sources is used to treat a variety of medical conditions in a multitude of specialties, including dermatology, ophthalmology, urology, otolaryngology, as well as others. Medical uses of light can be traced back thousands of years, and the use of light to treat a variety of skin disorders has continued throughout history. It was Albert Einstein who developed the concepts which ultimately laid the foundation for the development of the laser. Understanding fundamental atomic structure is essential in understanding how laser light is created and its unique characteristics. Over the past few decades, lasers have revolutionized how we treat a variety of skin and other medical conditions. In addition to their great benefit, however, these powerful devices have the potential to pose significant hazard to the patient and operator, making safety a crucial aspect of proper laser operation.

Brief Laser History

It was Albert Einstein who developed the concept of light travelling in waves of particles known as photons and of 'stimulated emission' [1], ultimately laying the foundation for the development of the LASER (acronym for light amplification by stimulated emission of radiation, coined by Gordon Gould).

The precursor to the laser was the MASER (microwave amplification by stimulated emission of radiation). The first maser was created by Charles Townes in 1954 [2] and further improved upon by James Gordon and Herbert Zeiger. The initial maser, however, was incapable of continuous output until Nikolai Basov and Alexander Prokhorov in Moscow created a new system that could release stimulated emission of excited atoms without falling to the ground state, thus maintaining continuous output. In 1964, Basov, Prokhorov, and Townes shared the Nobel Prize in physics for their fundamental work in the development of maser principles. Shortly after the development of the maser, scientists explored the possibility of stimulated emission in other regions of the electromagnetic spectrum, such as the optical and infrared regions. In 1958, Arthur Schawlow and Charles Townes proposed the first optical maser which was later renamed 'laser' [3].

In 1960, Maiman [4] created the first functional ruby laser excited by a xenon flash lamp. This laser, however, was only capable of pulsed operation, until shortly thereafter Peter Sorokin and Mirek Stevenson developed the first laser capable of continuous output. This uninterrupted beam was very effective in destroying the desired target tissue, but also exposed the surrounding tissue to prolonged periods of laser energy, resulting in excessive collateral damage leading to hypertrophic scarring and pigmentary changes. Mechanical shutters were then introduced to interrupt the laser beam, creating quasi-continuous lasers attempting to minimize adverse effects. In 1961, the technique of quality switching or 'Q-switching' was introduced by Fred McClung and Robert Hellwarth [5, 6]. This technique allowed for shortening of the pulse width to nanoseconds using an electro-optical shutter. The development of other lasers such as the argon, CO_2, Nd:YAG, pulsed dye, diode, and excimer lasers rapidly followed. In 1983, Rox Anderson and John Parrish [7] proposed the theory of selective thermolysis, revolutionizing cutaneous laser surgery. With careful manipulation of wavelength and pulse duration in relation to target relaxation time, lasers could now selectively target and destroy specific structures without damaging the surrounding tissues. This is crucial in the targeted laser treatment of vascular lesions.

Medical uses of light can be traced back to as early as 4000 BC when the ancient Egyptians recorded using sunlight coupled with a topical photosensitizer, such as parsley or other psoralen-containing plants, to aid in the repigmentation of vitiligo. The use of light to treat a variety of skin disorders has continued throughout history. In 19th century Europe, sunlight was used as a treatment for cutaneous tuberculosis, and UV light has been used from the early 1900s until the present day, with and without tar, as an effective treatment for psoriasis. Not surprisingly, dermatologists and ophthalmologists were the first to entertain the therapeutic possibilities of masers and lasers. Shortly after Maiman's creation of the first ruby laser, ophthalmologists began experimenting with the laser for photocoagulation of various retinal lesions [8]. In 1961, Leon Goldman, Chairman of the Department of Dermatology at the University of Cincinnati, founded the first biomedical laser laboratory. There he studied and described the selective destruction of pigmented structures in the skin, such as hair follicles, by the ruby laser [9]. He also published on the potential treatment of nevi, melanomas, and tattoos utilizing the ruby laser, as well as the treatment of vascular lesions using the argon and Nd:YAG lasers [10]. Given his vast contributions to the field of laser medicine, Goldman is honored by the American Society for Laser Medicine and Surgery as the 'father of lasers in medicine in the United States' [11].

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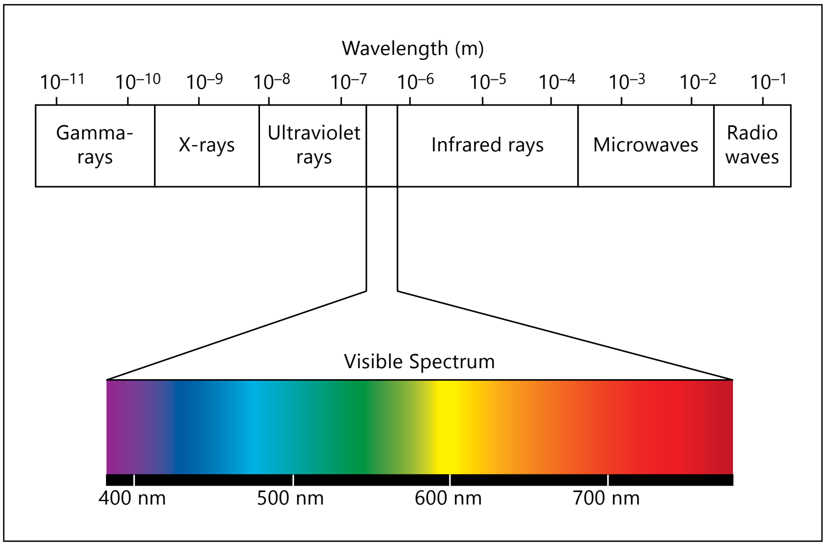

Fig. 1. The electromagnetic spectrum.

Basic Laser Physics

Properties of Light

All forms of energy are represented in the electromagnetic spectrum, which ranges from the short wavelengths of X-rays and gamma-rays to the long wavelengths of microwaves and radiowaves (fig. 1). Light is electromagnetic radiation composed of waves and energy packets known as photons and is in the visible wavelength region from 400 to 700 nm of the electromagnetic spectrum. Wavelength is determined by the distance between two successive troughs or crests of these waves. For the visible portion of the electromagnetic spectrum, the wavelength determines the color of the laser light. Frequency is determined by the number of wave crests or troughs that pass a given point in 1 s. The wavelength and frequency of light are inversely related to one another, obeying the equation $c = \lambda \cdot \nu$ in which $c = 299{,}792{,}485\ \mathrm{ms}^{-1}$, representing the speed of light in a vacuum. Therefore, shorter wavelengths of light have higher frequencies and more energetic photons than longer wavelengths of light, which have lower frequencies and less energetic photons.

For many years electromagnetic radiation from various sources has been used to treat a variety of medical conditions in a multitude of specialties, including dermatology, ophthalmology, urology, otolaryngology, as well as others. Currently, most lasers with medical applications generate light in the visible, infrared, or ultraviolet spectrum. Laser light within the visible spectrum creates a colored beam depending on the wavelength emitted. For example, the 532-nm KTP laser will produce a green beam while the 694-nm ruby laser will produce a red beam. Lasers that produce light outside of the visible spectrum (mid-infrared, infrared, or ultraviolet), such as Nd:YAG or CO_2 lasers, will produce an invisible beam.

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Unlike lasers, intense pulsed light devices are high-intensity broad-band light devices producing light consisting of many wavelengths, ranging from 500 to 1,300 nm. Therefore, these devices are usually equipped with cutoff filters in order to limit the emitted wavelengths to a narrower range to more precisely target a desired chromophore. Vascular lesions can best be targeted using filters emitting wavelength ranges of 500–670 or 870–1,400 nm corresponding to peaks of absorption on the absorption spectrum for oxyhemoglobin. Given the wide range of wavelengths that can be emitted by these devices, they are very versatile and can be employed in the treatment of a variety of targets such as vascular lesions, pigmented lesions, and hair. It can also increase efficiency by targeting multiple chromophores at once, for example one can simultaneously target both pigmented and vascular lesions associated with photoaging. However, when intentionally targeting just one chromophore, care must be taken that the other competing chromophore does not decrease the efficacy of the treatment of the intended target. Yet another benefit of intense pulsed light is the large spot size, allowing large areas to be treated more quickly. This is especially beneficial when intense pulsed light is used for hair removal.

Spontaneous and Stimulated Emissions

Understanding fundamental atomic structure is essential to understanding how laser light is created. According to Niels Bohr's atomic model, all atoms are composed of a central nucleus surrounded by electrons that occupy fixed energy levels or orbitals, giving the atom a stable configuration. Electrons can only jump from one orbit to another, and in doing so can emit or absorb energy. When an atom spontaneously absorbs a photon of light, the outer orbital electrons briefly move to a higher energy orbit. This is an unstable configuration and the atom rapidly and spontaneously releases a photon of light in order to return the electrons to their original stable lower energy orbital configuration. As the atom decays, the photon of energy emitted equals the difference in energy between the two orbits. Normally, spontaneous absorption and release of light occurs in a disorganized fashion, in all directions, producing incoherent light, unlike stimulated emissions.

In order for stimulated emissions to occur, a previously excited electron needs to absorb another photon of energy, which leads to emission of both photons upon returning to the ground state. The released photons will contain the exact same energy, frequency, and direction, and can stimulate emission of further photons. The increasing stimulation of photons will lead to a population of atoms in which there is a larger proportion of atoms in the excited versus the resting state. This is referred to as population inversion and is integral for the generation of laser light.

This synchronized photon release occurring with stimulated emission is responsible for the three unique characteristics of laser light, and it is these characteristics that differentiate it from other nonlaser light sources. These three main features are monochromaticity, coherence, and collimation. Monochromaticity refers to the fact that laser light is composed of a single wavelength or color, unlike white light which

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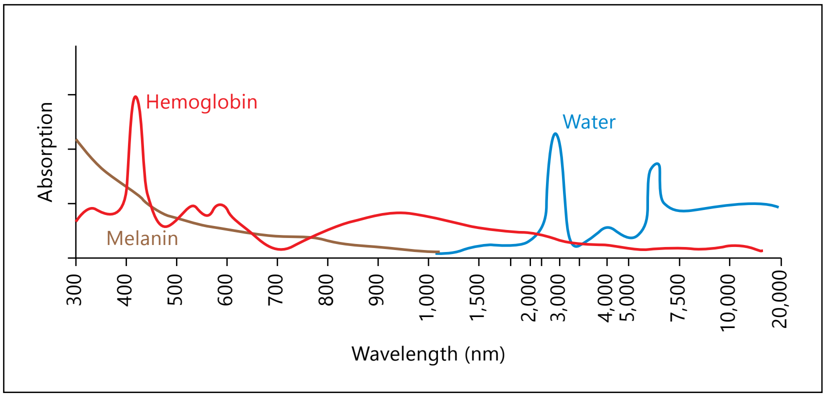

Fig. 2. Chromophore absorption curve.

is composed of a spectrum of wavelengths. This can be best exhibited by shining white light through a prism which produces a spectrum of colors. In contrast, when shining a laser light through a prism, only a single color, corresponding to the wavelength of the laser light, will be produced. Coherence refers to the fact that the light waves generated travel in phase with one another in regard to time and space. Collimation means that the transmission of light occurs in parallel fashion without significant divergence, even over long distances. This produces a narrow beam diameter, which does not change with changes in distance, allowing laser light to maintain its energy even over long distances.

Chromophores

The skin contains several chromophores, both endogenous and exogenous, that are able to absorb certain wavelengths of light. The three main endogenous chromophores in the skin are melanin, oxyhemoglobin, and water, and they are often targeted by a variety of lasers. Other endogenous chromophores are proteins and lipids. Each of these chromophores has an absorption spectrum with peaks at different wavelengths. The decision of which wavelength laser to utilize in the treatment of a particular lesion is based on these curves and peaks. The absorption spectrum form oxyhemoglobin ranges mostly from 400 to 600 nm with peaks at 418, 548, and 577 nm that can be specifically targeted in order to decrease absorption by competing chromophores (fig. 2). In contrast, the absorption curve for melanin is a subtly decreasing line ranging from 400 to 750 nm with no peaks. Water exhibits a gently increasing absorption curve ranging from 900 to 1,400 nm in the infrared portion of the electromagnetic spectrum. Tattoo pigment is the most common exogenous chromophore in the skin, with corresponding wavelengths depending on the color of the tattoo ink.

In choosing the most optimal wavelength at which to treat a lesion, one must take into consideration not only the absorption peaks of the target, but the location of the targeted structure in the skin as well. It is important to keep in mind that shorter wave-

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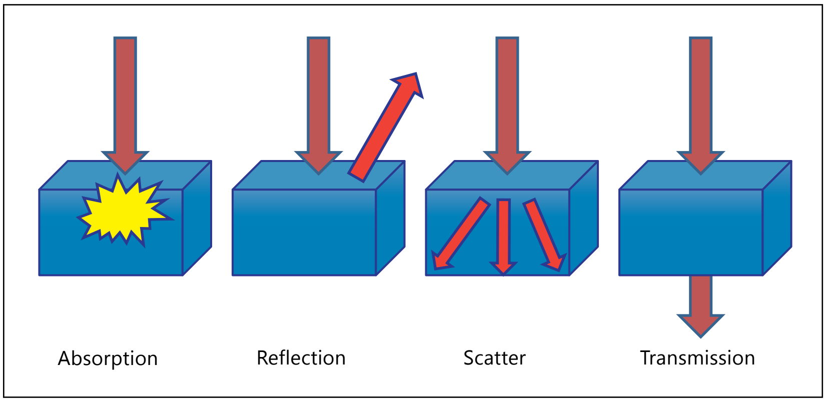

Fig. 3. Laser and tissue interactions.

lengths penetrate the skin more superficially while longer wavelengths have a greater depth of penetration. For example, while the absorption for melanin is greatest at shorter wavelengths, a laser at a shorter wavelength will be unable to penetrate to the dermis to reach its target, and treatment will likely be ineffective at that setting. As mentioned above, the absorption peaks for oxyhemoglobin range mostly between 400 and 600 nm; however, deeper vessels cannot be adequately targeted at these wavelengths, necessitating treatment with wavelengths capable of attaining a greater depth of penetration such as those emitted by the alexandrite, diode, and Nd:YAG lasers.

Laser Light Interaction with Tissue

Laser light can be absorbed, reflected, scattered, or transmitted upon interaction with the skin (fig. 3). A combination of these interactions typically occurs at any one time, the net effect of which affects laser impact and can vary based on the laser [12]. According to the Grotthus-Draper law, in order for laser energy to produce any biological effect in the skin, it must be absorbed. Absorption is the transformation of radiant light energy to a different form of energy, typically heat. It is only the light that is absorbed that is able to produce the desired effect in tissue. Light-absorbing targets in tissue are known as chromophores. Three main chromophores exist in skin: melanin, hemoglobin (or oxyhemoglobin), and water. The interaction of laser light with tissue is generally a function of the wavelength of the laser and whether it corresponds to the specific absorption spectrum of the targeted chromophore. Additionally, appropriate laser wavelength selection must also take into account the depth of the target structure in the tissue as longer wavelengths tend to have a greater depth of penetration. At wavelengths below 300 nm, there is strong absorption by protein, melanin, urocanic acid, and DNA. At wavelengths above 1,300 nm, penetration is shallow due to the absorption of light by water, the dominant chromophore at this end of the spectrum [13].

If the light is reflected from the surface of the skin, transmitted completely through the skin or scattered, no biologic effect will be produced. Most reflection occurs at the

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