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Neodymium: Yttrium-Aluminum-Garnet (Nd:YAG) Laser

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Abstract:

The Neodymium: Yttrium-Aluminum-Garnet (Nd:YAG) laser is a solid-state laser that uses neodymium ions (Nd^{3+}) doped into a yttrium-aluminum-garnet ($Y_3Al_5O_{12}$) crystal as the lasing medium. First developed in the 1960s, the Nd:YAG laser operates primarily at a wavelength of 1064 nanometers in the near-infrared spectrum. It is one of the most versatile and widely used lasers in both medical and industrial applications due to its deep penetration, high energy output, and ability to deliver energy precisely. In medical fields, the Nd:YAG laser has been extensively employed in dermatology, ophthalmology, urology, oncology, and surgery, owing to its ability to coagulate, vaporize, or ablate tissues with minimal damage to surrounding structures. In ophthalmology, for instance, it is commonly used for posterior capsulotomy and laser iridotomy, while in urology, it is applied in procedures like prostate vaporization and stone fragmentation. Its deep tissue penetration also makes it useful in treating vascular lesions and performing endoscopic surgeries. The Nd:YAG laser can operate in continuous or pulsed modes, allowing for precise control over energy delivery. When used in Q-switched mode, it delivers high-intensity pulses in very short durations, making it suitable for tattoo removal, pigmented lesion treatment, and laser skin resurfacing. Overall, the Nd:YAG laser's effectiveness, safety profile, and adaptability have made it an essential tool in modern therapeutic and surgical procedures.

Introduction

Laser, an acronym for "Light Amplification by Stimulated Emission of Radiation," is a revolutionary technology rooted in Einstein's quantum theory of radiation. Theodore H. Maiman's breakthrough achievement on 7th July 1960 marked the birth of the first functional laser, employing a ruby crystal as the lasing medium and intense flashes of light to stimulate emission **(Patil & Dhami, 2008)**. This initial success paved the way for the development of other solid-state laser systems, such as the neodymium:yttrium-aluminum-garnet (Nd:YAG) laser, that is capable of generating four primary wavelengths: 1064 nm, 1318 nm, 1444 nm, and 946 nm **(Houk & Humphreys, 2007; Šulc & Jelínková, 2013).**

Gaseous media, including argon, helium-neon, and carbon dioxide (CO2), provided alternative platforms for laser amplification, offering a departure from the solid glass rods used in early laser systems **(Houk & Humphreys, 2007)**.

Laser Properties

Laser beam exhibits distinct properties that differentiate it from ordinary light, these properties include:

- **Monochromaticity:** Laser beam consists of a single wavelength of color, determined by the gain medium.
- **Collimation:** The photons within a laser beam are parallel to each other. So all light energy is used in one direction allowing laser to transfer majority of output power even at longer distances.
- **Directionality:** Laser beam travels in a tight, focused beam towards one direction.
- **Coherence:** Laser waves are synchronized, maintaining a stable wavefront. This property allows for minimal diffraction, enabling the beam to travel long distances without significant spreading **(Svelto et al., 2007; Sener, 2012)**.

Laser components

A laser system typically consists of several key components, that are common to most laser designs:

1. Gain Medium: The material within which stimulated emission occurs. This can be solid (e.g., ruby, neodymium), semiconductor (e.g., gallium arsenide), liquid (e.g., organic dyes), or gas (e.g., argon, carbon dioxide). The choice of gain medium determines the laser's output wavelength.

2. Pump Source: Provides the energy required to excite atoms in the gain medium, creating a population inversion. This condition is essential for stimulated emission to dominate over spontaneous emission and generate coherent light. Pump sources can be optical (e.g., intense light sources) or non-optical (e.g., electrical discharge, chemical reactions).

3. Optical Resonator: A cavity formed by two mirrors that confines and reflects light, maximizing the number of passes through the gain medium.

4. Output Coupler: A partially reflective mirror that allows a portion of the amplified light to escape as a laser beam **(Stenhoff & Mills, 2024)**.

Laser-Tissue Interactions

When laser beam interacts with an object, such as the skin suface, it undergoes a combination of four primary physical processes: absorption, reflection, transmission, and scattering. The outcome of this interaction depends on the object's physical properties and the parameters of the laser beam **(Alhallak et al., 2021)**.

Selective photothermolysis

Anderson & Parrish (1983) stated that selective photothermolysis involves targeting a specific chromophore within a lesion while minimizing thermal damage to surrounding tissues. To achieve this, three essential elements are required:

1. Wavelength: The laser must emit light at a wavelength that is preferentially absorbed by the targeted chromophore.

2. Fluence: The energy delivered by the laser beam must be sufficient to damage the target tissue.

3. Pulse Duration: The duration of the laser pulse must be shorter than the thermal relaxation time (TRT) of the chromophore. This ensures that heat is not conducted away from the target tissue before significant damage occurs **(Anderson & Parrish, 1983).**

Visible light lasers, such as pulsed dye, Q-switched ruby, Nd:YAG, and alexandrite lasers, were developed based on the principle of selective photothermolysis. These lasers target primary cutaneous chromophores, including melanin and oxyhemoglobin **(Carroll and Humpherys, 2006).**

Thermal relaxation time (TRT) is the duration required for a chromophore to cool to half of its peak temperature following laser irradiation. TRT is directly proportional to the chromophore's size, meaning smaller targets cool more rapidly than larger ones **(Stewart et al., 2013)**.

Chromophores can also serve as subsurface heat sources, denaturing adjacent tissue targets. This phenomenon, known as **extended selective photothermolysis**, is particularly applicable in hair removal and the treatment of telangiectasias (dilated blood vessels). By selectively targeting a chromophore within a lesion, laser energy can be harnessed to heat and destroy surrounding tissue, achieving a broader therapeutic effect **(Altshuler et al., 2001)**.

Cooling devices

While selective photothermolysis enables precise targeting of a chromophore, some degree of energy absorption by competing chromophores and heat transfer to unintended tissues may still occur. Epidermal damage, often caused by excessive absorption of energy by epidermal melanin, is a common challenge in laser treatment. In darker skin types, where epidermal melanin absorbs more energy, blistering and scarring can result. To decrease these risks, skin cooling devices have been developed to protect the epidermis during laser procedures (**Zenzie et al., 2000).**

Skin cooling techniques can be strategically applied before, during, or after laser treatment to minimize thermal damage and enhance patient comfort. Pre-cooling involves cooling the epidermis prior to laser application, while parallel cooling occurs simultaneously with the laser pulse. Post-cooling is applied after the laser procedure to reduce pain and edema. Skin cooling techniques can be categorized into two primary methods:

1. Contact cooling involving direct contact between a cooling device or substance and the skin. This can be achieved actively using copper or sapphire tips, or passively using materials like ice or cold gels. In both cases, heat is transferred from the warm skin surface to the cooling agent, thereby reducing the temperature of the treated area.

2. Non-contact cooling utilizing either evaporation or convection to remove heat from the tissues. Cryogen spray or cold air are commonly employed methods for non-contact cooling **(Das et al., 2016)**.

Nd:YAG laser applications in dermatology

Nd:YAG laser is recognized as one of the most advanced tools in dermatological laser therapy. Its efficacy varies based on wavelength (1064 nm, frequency-doubled 532 nm) and operational modes (continuous, Q-switched, long-pulsed), enabling the treatment of a broad range of benign pigmented lesions, including tattoos, nevus of Ota, café-au-lait macules, and lentigines, as well as vascular anomalies such as hemangiomas, port-wine stains, essential telangiectasias, and angiomas. Furthermore, Nd:YAG laser has been occasionally employed in the management of Kaposi sarcomas and epithelial skin tumors **(Greve & Raulin, 2000)**.

For laser hair reduction, long-pulsed Nd:YAG laser is considered the safest laser option for individuals with darker skin types (Fitzpatrick IV-VI) and black hair due to its longer wavelength. This longer wavelength allows for deeper penetration into the dermis, reducing the risk of melanin absorption in the epidermis reducing the likelihood of side effects in darker-skinned patients **(Sari et al., 2023)**.

Several studies have demonstrated the efficacy of long-pulsed Nd:YAG laser in the treatment of striae rubrae, with results superior to other laser options including pulsed-dye laser and CO2 fractional laser **(Zhu et al., 2024)**. Nd:YAG 1064nm laser acts by targeting oxyhemoglobin within striae, resulting in reduced erythema. It also stimulates collagen synthesis, improving skin atrophy and overall appearance **(Kravvas et al., 2019)**.

Hendawy et al. (2021) observed improvement in striae appearance with significant decrease in both width and length after 3 sessions of Nd:YAG laser using parameters of 80 J/cm^2 fluence, 4-mm spot size and 15-ms pulse duration. They also reported increased epidermal thickness and dermal collagen on histopathological aspect.

Elsaie et al. (2016) also conducted a study comparing between two fluences of long-pulsed Nd:YAG for the treatment of striae. They concluded that 75 J/cm2 fluence gave better results in striae rubrae with increased dermal collagen and elastic fibers, whereas 100 J/cm2 fluence was better for striae albae.

Laser complications

Some patients may experience temporary reactions such as erythema, urticaria, acne-like eruptions, petechiae, or whitening of fine hair. These transient effects do not necessitate treatment discontinuation. However, serious complications, including post-inflammatory hyperpigmentation, mottling hypopigmentation, leucoderma, severe urticaria, severe acneiform eruptions, and herpes simplex activation, necessitate immediate suspension of treatment **(Polnikorn, 2008; Kravvas et al., 2019)**.

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