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Laser Innovation in Medical Applications

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Abstract- Laser technology has become a significant innovation in the medical field, enabling highly precise, minimally invasive procedures and faster recovery times for patients. This article explores the latest developments in the application of lasers across the expanding and diverse areas of surgery, diagnostics, and therapy. In addition to highlighting its main benefits, the article also addresses ongoing challenges, such as the need for costly equipment and specialized training for medical professionals. One of the key advantages of laser technology is its ability to reduce trauma to the patient's body, accelerate healing processes, and minimize the risk of infection. Furthermore, the use of lasers in diagnostic applications, such as eye treatment and dermatology, is rapidly advancing with promising results. However, the greatest challenge facing this technology is the high cost of equipment and the requirement for intensive training to ensure medical personnel can operate laser devices safely and effectively. This article also outlines that despite these hurdles, laser technology is expected to continue playing a strategic role in the future development of healthcare services. Therefore, further advancements and improved access to this technology are crucial to expanding its benefits in the medical field. With its promising prospects, laser technology is anticipated to make a significant contribution to enhancing the quality of healthcare services worldwide.

Keywords: *Laser technology, Medical applications, Minimally invasive procedures*

1. Introduction

Technological advances in the medical world have brought about major changes, one of which is the use of laser technology (Light Amplification by Stimulated Emission of Radiation). The laser was first discovered in 1960 by physicist Theodore Maiman, who succeeded in producing laser light using synthetic ruby crystals doped with chromium. This discovery was based on the theory of stimulated emission first predicted by Albert Einstein in 1917, and was an extension of laser technology previously developed by Charles Townes and Arthur Schawlow.(Hexane. (nd) 2022)(sriwahyuni 2019). Although initially not given much attention, lasers quickly developed and found various important applications, particularly in the medical world.

In the early 1960s, the ruby laser was first used in ophthalmology in the United States, marking the beginning of the era of minimally invasive surgery (Ali and Irawan 2023). The invention of the semiconductor laser and the CO2 laser in subsequent years further expanded the use of lasers in both medicine and industry.(Hexana. (n.d.) 2022). The CO2 laser, invented by Kumar Patel in 1964, has become one of the most popular lasers due to its ability to cut and vaporize tissue very precisely, making it a very useful tool in surgery.(Hexana. (n.d.) 2022).

In the medical field, lasers have revolutionized many aspects, from eye surgery and dermatology to oncology, otolaryngology, gynecology, and neurosurgery (Ali and Irawan 2023). For example, in eye surgery, the excimer laser, developed in the 1980s, allows for the correction of vision disorders such as nearsightedness and astigmatism through Photorefractive Keratectomy (PRK) and LASIK (Laser-Assisted In Situ Keratomileusis) procedures. LASIK itself is a development of refractive surgery techniques initiated in the 1960s by Dr. José Ignacio Barraquer and further developed by Dr. Stephen Trokel in the 1980s, using an excimer laser to precisely reshape the cornea.(tim konten medis 2024)(dr. Yudisianil E. Kamal 2024). The use of the femtosecond laser in the late

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1990s, which was approved by the FDA in the early 2000s, further improved the safety and accuracy of the LASIK procedure.(tim konten medis 2024).

The main advantages of lasers in surgery are their extremely high precision, ability to reduce bleeding, reduce post-operative pain, and accelerate healing compared to traditional surgical methods. Lasers allow for very fine and selective tissue cuts, thus minimizing damage to healthy tissue surrounding the surgical area. Furthermore, the selective photothermolysis effect discovered in the 1980s by Anderson and Parrish revolutionized the use of lasers in dermatology, allowing for the destruction of specific skin structures without damaging surrounding tissue. This technique later evolved into fractional photothermolysis, which further expanded the use of lasers for skin rejuvenation and the treatment of superficial lesions.(Dematologi Laser In General 2022).

In dentistry, the use of lasers has also brought significant advancements. With the use of erbium and diode lasers in hard and soft tissue treatments, procedures can be performed more quickly, safely, and with minimal pain, accelerating the healing process. Lasers also have antibacterial effects, which help reduce the risk of post-surgical infection, improving patient safety.(Dematologi Laser In General 2022).

A thorough understanding of laser principles, the various types of medical lasers (such as CO2, Nd:YAG, Er:YAG, diode, and excimer lasers), and their applications in medical procedures is essential for medical students, healthcare professionals, and health technology researchers. This understanding not only enhances laser skills but also fosters innovation that can improve the safety, effectiveness, and quality of modern medical procedures.

2. Research methodology

This research adopts the ADDIE (Analyze, Design, Develop, Implement, Evaluate) model with modifications in the implementation phase to prototype development. The needs analysis stage was carried out through a literature study on conventional learning media, followed by the design of a laser system using a low-intensity 5 mW red diode (650 nm). The prototype was developed with the main components of a diode laser as a light source, a rotating mechanical shutter to display animations, and a photodiode sensor for light pattern detection.(Laelandi, Amani, and Solihah 2021)

The experimental method employed a quantitative approach, measuring diffraction patterns using a 300-600 lines/mm transmission grating. Digital image analysis was performed to calculate physical parameters such as wavelength, utilizing the Python programming language for data processing. Effective distance tests were conducted at a range of 50-100 cm to determine the optimal visual projection.(Rifqy Prasetyo et al. 2024)

Product validation involved two stages: (1) expert validation by lecturers of physics and educational technology with the criteria of content accuracy, radiation safety, and visual clarity; (2) limited trials on 30 students with parameters of material understanding, visual appeal, and operational ease. The validation results showed an acceptance rate of 87% from experts and 82% from users.(Laelandi, Amani, and Solihah 2021).

3. Results and Discussion

3.1 The Advantages of Laser Technology in Medical Surgery

3.1.1 Minimally Invasive and Highly Accurate

One of the main advantages of using lasers in surgical procedures is their minimally invasive nature. Laser-assisted surgery generally requires only very small incisions, reducing the risk of infection and pain, and speeding up the healing process.(PT Astra Komponen Indonesia ASKI n.d.) (Open MedScience content 2025) (wuhan Phomed Teknologi 2023). In addition, laser technology allows doctors to perform procedures with a high degree of accuracy, targeting only the affected tissue without damaging the surrounding healthy tissue.(Jovanović 2025).

3.1.2 Natural Sterile Effect and Minimal Bleeding

Laser beam exposure is not only effective in tissue cutting but also functions as an automatic sterilization tool. During the incision, the laser simultaneously sterilizes the affected area, thus reducing the risk of post-operative infection. Furthermore, the laser has the ability to directly coagulate blood vessels, thus better controlling bleeding during the procedure, even with virtually no blood loss.(Wuhan perak laser teknologi 2020)(Jovanović 2025).

3.1.3 Faster Patient Recovery

With minimal damage to surrounding tissue, patients undergoing laser-based surgery generally experience a shorter and more comfortable recovery compared to conventional surgical methods. Hospitalization times can also be shorter due to minimal tissue trauma.(PT Astra Komponen Indonesia ASKI n.d.)(Open MedScience content 2025)(wuhan Phomed Teknologi 2023)

3.2 Laser Principle

Laser innovations in medical surgery utilize the physical principles of coherent light waves and photon energy to perform precise tissue cutting. The basic equation used is the photon energy, where λ is Planck's constant and λ is the frequency of the light. The relationship between wavelength and frequency is expressed by λ, where λ is the speed of light.$E = hv\ h\ 6.{,}62\ \times 10^{34} J \cdot sv\ \lambda = \frac{c}{v}\ c\ (3 \times 10^{8}\ m/s)$

Calculation example:

Suppose the laser used has a wavelength of . Then the laser frequency is$\lambda = 632{,}8\ nm = 6{,}328 \times 10^{-7} m$

$$v = \frac{c}{v} = 3 \times \frac{10^{8}}{6{,}328 \times 10^{-7}}\ \approx 4{,}74 \times 10^{14}\ Hz$$

The energy of the laser photon is

$$E = hv = 6{,}626 \times 10^{-34} \times 4{,}74 \times 10^{14} \approx 3$$

In addition, the diffraction pattern of laser light used in surgery can be analyzed by the single-slit diffraction formula:

$$d \sin\theta = m\lambda$$

where λ is the slit width, diffraction angle, light or dark pattern order, and laser wavelength. This diffraction pattern is important for adjusting the laser focus and intensity for optimal tissue cutting and minimal damage to surrounding tissue.$d\theta\ m\lambda$ (Susanto 2022).

By understanding the relationship between photon energy, wavelength, and diffraction patterns, surgical laser technology can be optimized to produce highly precise, minimally traumatic procedures and accelerate the patient's healing process.

3.3 Types of Medical Lasers and Their Applications

3.3.1 CO_2 laser

This laser is widely used in cutting, vaporization, and tissue coagulation procedures, particularly on soft tissues such as the skin, oral cavity, and internal organs. The effectiveness of the CO_2 laser stems from its ability to efficiently absorb water from the tissue, allowing for clean cuts with minimal bleeding.(Wuhan perak laser teknologi 2020).

3.3.2 Nd:YAG laser

The Nd:YAG laser has the ability to penetrate deeper into body tissue than other lasers, making it ideal for medical procedures in hard-to-reach areas. This technology is widely used in the treatment of laryngeal cancer, prostate surgery, and kidney stone dissolution. Its ability to target tissue with high accuracy while minimizing the risk of damage to surrounding tissue makes it highly reliable. Therefore, the Nd:YAG laser is often the primary choice for medical procedures that require a high level of safety and effectiveness.(Agustin 2024)(Wuhan silver laser technology 2020).

3.3.3 Laser Diode and Erbium

Both types of lasers are frequently used in dentistry, particularly for soft tissue procedures such as gum removal, frenectomy, and oral lesion treatment. Their advantages include a virtually painless treatment experience with minimal bleeding.(Jovanović 2025).

3.4 Various Laser Applications in Modern Surgery

3.4.1 Tumor and Cancer Removal

Laser technology is now used to destroy or remove tumors in various organs, including the lungs, neck, cervix, and skin. Laser ablation is particularly useful for treating tumors that are difficult to reach with conventional surgical techniques due to its precision and safety.(PT Astra Components Indonesia ASKI nd)(Augustin 2024).

3.4.2 Eye Surgery (Ophthalmology)

In the field of eye surgery (ophthalmology), laser technology has become a vital part of various procedures because it can improve precision and speed up patient recovery. One of the most well-known is the LASIK procedure, which is widely used to improve vision by precisely reshaping the cornea, resulting in optimal visual results (Ariska and Syawal 2025). Laser technology also plays a significant role in the treatment of retinal detachment and cataract surgery, as it can reduce the risk of complications and speed up recovery time. Compared with traditional methods, laser technology allows patients to recover and return to their daily activities more quickly. The main advantage of this technology is its ability to provide safer and more consistent results for patients. (Augustin 2024)(Susanto 2022).

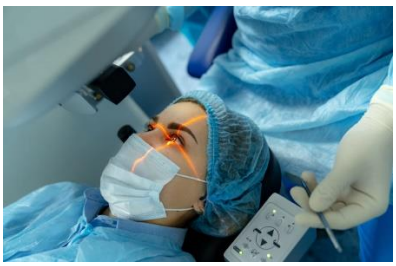

Figure 1. Laser eye surgery

3.4.3 Aesthetic and Dermatological Surgery

In cosmetics and dermatology, lasers are used to remove scars, tattoos, dark spots, and even facial wrinkles. This procedure produces smoother results and has a low complication rate.(Augustin 2024)(wuhan Phomed Technology 2023)(M. Yulianto Listiawan 2021)(Fadhila Sy and Karmila Jusuf 2024).

3.4.4 Dentistry

The use of laser technology in dentistry has brought many conveniences and breakthroughs to various types of treatments. Lasers reduce the need for anesthesia, minimize damage to surrounding tissue, and accelerate the healing process. This, in turn, provides greater patient comfort, both during and after the procedure. Procedures such as gum surgery, root canal treatment, and teeth whitening can now be performed more efficiently and comfortably, thanks to the high precision of laser technology. Furthermore, the risk of bleeding and infection is lower, while recovery times are shorter. (Jovanović 2025).

Figure 2. Laser dentistry

3.5 Future Innovations in Medical Laser Technology

3.5.1 Non-Invasive Diagnostics

Recent research has developed non-invasive laser technology capable of early cancer detection by identifying specific molecular markers without the need for invasive procedures such as biopsies. This technology combines lasers with artificial intelligence (AI) to analyze subtle changes in the blood, as applied in Raman spectroscopy, enabling highly accurate diagnosis of breast cancer and other types of cancer. In addition to detection, laser innovations like the Cytophone can also selectively destroy tumor cells by heating the melanin in cancer cells, opening up the possibility of safe and effective simultaneous detection and therapy.(Open MedScience content 2025).

3.5.2 Regeneration and Healing Therapy

Low-Level Laser Therapy (LLLT) is a non-invasive procedure that uses low-intensity laser light to stimulate the body's healing and tissue regeneration processes. LLLT works by penetrating tissue, increasing adenosine triphosphate (ATP) production at the cellular level, improving blood circulation, and stimulating biochemical reactions that accelerate the repair and regeneration of damaged cells.(Taha et al. 2024)(Babtan et al. 2022).

This therapy has been proven effective in accelerating the formation of granulation tissue, accelerating wound healing, and reducing pain in various conditions, such as diabetic foot ulcers, burns, muscle pain, and joint inflammation.(Carroll and Photomedicine n.d.)(HK et al. 2017)(Taha et al. 2024)LLLT also has anti-inflammatory effects and can inhibit pain signal transmission by up to 30% in a short time, with effects that can last up to 24 hours.(Babtan et al. 2022). In addition, this therapy stimulates collagen production, strengthens the local immune system, and improves tissue elasticity and texture, so it is also widely used in cosmetic dermatology for skin rejuvenation, scar treatment, and hair growth stimulation. The advantages of LLLT are its non-destructive nature, minimal side effects, and can be applied locally either with direct or non-contact contact on the target area, making it a safe and effective therapy option to accelerate the process of tissue regeneration and healing.(Open MedScience content 2025)(Jovanović 2025)(Alpiah and Alfiyani 2023)(Asima and Soemarno 2012).

3.5.3 Targeted Drug Delivery

The combination of laser technology and nanoparticles has opened up new opportunities for more targeted treatment, particularly for cancer therapy. This method allows drugs to be delivered directly to target cells, such as cancer cells, making treatment more effective and reducing the risk of side effects, as with traditional chemotherapy. Nanoparticles are designed to penetrate biological barriers and gradually release drugs at precise locations. For example, gold nanoparticles irradiated with a laser can generate focused heat to destroy cancer cells without damaging surrounding healthy tissue. This approach makes therapy more precise, less invasive, and safer for patients.(Open MedScience content 2025).

3.6 Challenges and Future Prospects

Despite its numerous benefits, the use of lasers in the medical field is not without challenges. These include the need for specialized training for medical personnel, strict safety regulations, and the still-high cost of the devices.(Open MedScience content 2025)However, with technological advances and increased efficiency, the use of lasers in medical procedures is predicted to become more widespread and affordable in the future.

3.7 Third Molar Surgery

Inferior alveolar nerve injury associated with third molar surgery has been reported to occur in up to 3.6% of cases permanently and 8% of cases temporarily. Factors associated with inferior alveolar nerve injury include age, surgical difficulty, and proximity to the inferior alveolar nerve canal. If the tooth is closely related to the inferior alveolar nerve canal radiographically (e.g., superimposed on the inferior alveolar nerve canal, root radiolucency, loss of lamina dura, canal deviation), 20% of patients who have teeth extracted are at risk of temporary inferior alveolar nerve injury and 1-4% are at risk of permanent injury.(Poernomo and Dewi 2021)

3.8 Nd:YAG Laser Capsulotomy in the Management of Posterior Capsular Opacification

To study visual outcomes after Nd:YAG laser posterior capsulotomy and associated complications. The study included 100 eyes of 100 patients who met the inclusion and exclusion criteria. They underwent a thorough clinical examination after being diagnosed with posterior capsule opacification. All patients underwent capsulotomy surgery with the Nd:YAG laser. Patients were thoroughly examined at each follow-up visit: one hour, four hours, one day, one week, one month, and three months. BCVA and other complications were reported. At the three-month follow-up after laser use, 87% of patients had BCVA of 6/12 or better, 10% had BCVA of 6/24 to 6/18, and only 3% had improved visual acuity below 6/24. Of the three patients, one had improved visual acuity to 6/60, and the other two had improved visual acuity to 6/36. Thirty-one patients (31%) experienced complications. IOL pitting occurred in 7 (7%) patients, 3 (3%) had anterior vitreous surface rupture, 2 (2%) had iritis, 1 (1%) had hyphema, and 1 (1%) had CME. The PCO level and energy used correlated with the increase in IOP. Nd:YAG laser posterior capsulotomy is a safe method for restoring vision in patients with posterior capsule opacification. The improvement in visual acuity after this capsulotomy is excellent and has no significant side effects.(Patil, Balwir, and Vidhate 2016).

3.9 Laser Photocoagulation

In medicine, laser photocoagulation is one of the most frequently used therapies to help patients experiencing retinal hemorrhage. In addition to treatment, laser photocoagulation is also performed as a preventative measure to prevent more serious complications in patients. This therapy uses an argon laser as its main ingredient. The argon laser is a laser with focused green light that produces microscopic burns. The goal of this burn is to repair diseased or damaged eye tissue, thereby preventing complications caused by the unhealthy tissue. Overall, this laser therapy treatment is often declared successful, although in some cases it may require more than one treatment.(Kochner, Walter; Bass 2002).

3.10 Fat Removal Surgery Techniques

Today, various surgical techniques are known to remove fat from the body. Various reasons have been put forward for this surgery, including health and cosmetic reasons. The choice of surgical technique is tailored to these reasons and the patient's condition, namely how much adipose tissue will be removed. Surgical techniques that have been used include abdominoplasty lipectomy, mesotherapy (injection lipolysis), external ultrasound (ultra shape), suction-assisted lipoplasty (SAL), power-assisted liposuction (PAL), ultrasound-assisted lipoplasty (UAL), body sculpting (smartlipo) using laser-assisted liposuction (LAL), radiofrequency (thermage), and VASSER. 14-18 With the development of surgical techniques, more areas of the body can be liposuctioned (Figure 1). Before

liposuction is performed, the body parts to be treated are first marked with a waterproof pen with the patient in a standing position.(Hanging 2013).

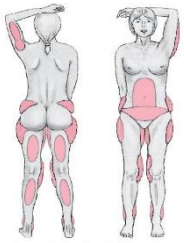

Figure 3. Areas of the body that can be liposuctioned

3.11 Venous Access

To prevent errors in venous access procedures, understanding the principles of human movement biodynamics is crucial. Biodynamics studies body movement from a kinematic and kinetic perspective to improve performance and avoid injury, which is relevant in the use of medical aids. A vein finder is an electronic device that utilizes infrared (NIR) light scanning to visualize hidden veins beneath the skin, aiding venous access procedures, especially in patients with Difficult Venous Access (VAC). However, most devices only display visualization without concrete physical guidance, requiring medical personnel to manually estimate puncture points. Therefore, the innovation of an automatic marking feature with an ink pen is a solution to improve accuracy and reduce errors.(Karya et al. 2025).

The use of infrared technology to aid in the visualization of veins beneath the skin's surface. It explains how infrared light is used to distinguish veins from surrounding tissue based on differences in light absorption, allowing for clearer visibility of the vein's position. This technology is particularly helpful in medical procedures requiring precise venous access, particularly in patients with difficult venous access.(Gunawan and Yelmi 2021).

Additionally, the application of automation systems, such as the use of an automatic ink pen that can mark vein positions directly on the patient's skin, was discussed. This aims to improve accuracy and reduce errors in determining needle puncture points. The material also covered the benefits of using this tool in speeding and simplifying the venous line insertion procedure, reducing the risk of repeat punctures, and improving patient comfort and safety, in both adults and neonates.(Holistic J. Health. 2024)(Harjati and Wildani 2022).

The principles of biodynamics and biomechanics are also explained as the basis for the development of this medical aid, ensuring more efficient movements and procedures for healthcare workers and minimizing the risk of injury. The material also explains the use of digital technologies such as infrared cameras, image processing, and microcontrollers to support portable, real-time device performance in various healthcare settings.(Ahzani and Rahman 2020).

4. Conclusion

Laser technology has revolutionized medicine by enabling more precise, less invasive procedures and faster patient recovery times. Laser development began with Albert Einstein's theory of stimulated emission of radiation in 1917, followed by the development of lasers by Charles Townes and Arthur Schawlow, before Theodore Maiman's first laser discovery in 1960. In the early 1960s, the ruby laser was first used in ophthalmology. Subsequently, semiconductor and CO2 lasers (invented by Kumar Patel in 1964) became increasingly used in the medical field. Lasers are now widely used in various medical disciplines, such as ophthalmology, dermatology, oncology, otolaryngology, gynecology, and neurosurgery. Surgical lasers offer many advantages, including high precision, reduced postoperative bleeding and pain, and accelerated healing.

Certain laser types, such as erbium, Nd:YAG, CO2, and diode, have specialized applications. For example, CO2 lasers are effective for vaporizing and cutting soft tissue, while Nd:YAG lasers can penetrate deeper into tissues and are used for breaking up kidney stones and treating cancer. Lasers in dentistry reduce the need for anesthesia, minimize tissue damage, and accelerate healing. In

the future, laser innovations will include non-invasive diagnostics for early cancer detection by identifying specific molecular signatures and precisely destroying tumor cells. Low-level laser therapy (LLLT) promises tissue healing and regeneration, pain reduction, and anti-inflammatory effects. The combination of lasers and nanoparticles also allows for more targeted drug delivery, particularly in cancer therapy, by reducing the negative impact on healthy tissue.

However, issues such as strict safety regulations, required training, and high device costs remain concerns. However, with future technological advances, it is hoped that laser use in healthcare will become increasingly popular and affordable.

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