Current Trends and Future Directions of Laser-Tissue Interaction Physics in Dentistry: A Focus on Saudi Arabia

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Abstract

The application of laser technology in dentistry has revolutionized the field by introducing minimally invasive and precise treatment methods. Laser-tissue interaction physics provides the foundation for understanding how laser energy interacts with oral tissues, including soft tissues, teeth, and bone. This paper explores the fundamental principles of laser-tissue interaction, focusing on photothermal and photomechanical effects, and examines their diverse applications in dental procedures such as cavity preparation, periodontal treatment, and teeth whitening. It also highlights the advancements in laser technology, challenges, and adoption trends in Saudi Arabian dentistry. Emphasis is placed on emerging innovations, such as the integration of artificial intelligence, nanotechnology, and biomaterials, which promise to enhance the effectiveness and safety of laser-based treatments. The review concludes with recommendations to overcome current limitations, improve accessibility, and foster research and education to integrate laser technology effectively into modern dental practices.

Keywords :Laser-tissue interaction, dentistry, laser applications, photothermal effects, photomechanical effects, dental technology, Saudi Arabia, artificial intelligence, nanotechnology, biomaterials.

1. Introduction to Laser-Tissue Interaction Physics in Dentistry

Laser-tissue interaction physics in dentistry has been of prime interest to dental researchers. Laser has a distinct meaning when a dentist utilizes it in various dental procedures. It follows the principles of physics and has been studied under the rubric of laser-tissue interaction for a long time. The therapeutic benefits of laser application in soft tissue management have allured clinical practitioners towards its usage. Lasers are also biocompatible, meaning that they enhance the biologically reparative effects and reduce the risk of iatrogenic impacts as well. Similarly, understanding the "why" and "how" of these reactions has become mandatory to innovate clinical practices in dentistry. (Coluzzi et al.2021)(Detection2022)(Brown, 2020)(Singh & Melnik, 2020)

Since the 1960s, the advent of lasers has opened new horizons in various fields of science. The first paper on the application of laser light in dental surgical procedures was published in 1960. Since then, numerous studies have been conducted untangling the utility of lasers in dentistry across the globe. There are different types of lasers, and each has specific characteristics of wavelength and ablation factor; accordingly, their usage is prevalent in dentistry. These lasers also have distinctive capabilities to interact with oral tissue due to the inclusion or exclusion of hard tissue ablation. The role of the highly beneficial field of dentistry, i.e., laser-tissue interaction, will be the next subject of interest for dentists willing to sharpen their clinical knowledge. The practicability of such applications, especially in a diverse country like the Kingdom of Saudi Arabia, needs to be inquired into in future directions with a broader perspective. (Paschoal et al.2022)(Rajan and Muhammad2021)(Maheshwari et al.2020)(Liaqat et al.2022)(Coluzzi et al.2021)

1.1. Fundamentals of Laser-Tissue Interaction

The interaction between the laser and surrounding tissues can be understood through the study of light behavior and individual cellular responses. Laser light has unique physical characteristics with its distinct waves of light organized by their spacing and direction. The fundamental properties of laser radiation include monochromaticity, coherence, and directionality. Tissues display some selected responses when exposed to lasing activities. The focal point is frequently ablative, and the liquefaction area is superficial. Optical breakdown, mechanical shockwave, and tiny plasma scatter can be seen intracellularly. Around this layer, there is a sharp rim of vascular stasis. Light also elicits primary—acute—biological responses such as potentiation of transcription. Finally, lasers appear to be more accurate. The absorption of laser light into tissue is very wavelength-dependent when that light interacts with water, hydroxyapatite, hemoglobin, and melanin, removing related tissues selectively in numerous surgical and dental procedures. Primary absorption is the preferred mechanism of light interaction, although a secondary scattering nevertheless occurs. (Aldalawi et al.2023)(Lanka et al.2022)(Shanshool et al., 2022)(Hamdy & Mohammed, 2022)(Hanke et al., 2021)(Shimojo et al.2020)(Kim & Darafsheh, 2020)

Almost all oral tissues, including soft tissues, teeth, and bone, can absorb laser light during a range of wavelengths. The most often utilized soft tissue wavelengths used in dentistry are invisible infrared and visible red wavelengths. Based on their main chromophore absorption, these wavelengths may provide laser energy to soft tissues through photothermal interactions, targeting demand, and regulating precise depths of therapeutic penetration. In visible spectral ranges, light-induced photochemical phenomena may also occur. Photothermal and photochemical interactions may be recognized based on the prevailing phenomenon. The outcomes of the two photo-mechanisms are extremely diverse, but the safety precautions are still the same. (Parker et al.2020)(Convissar, 2020)(Coluzzi et al.2021)(Pandarathodiyil & Anil, 2020)(Alaa, 2020)(Tenore et al.2023)(Kaub & Schmitz, 2022)(Altayeb et al.2021)

Magnification targets the light to the size of a minibeam. Both photothermal and photomechanical reactions have a surface interaction area and a micrometer size when they reach the tissue. Targeting an even tinier parasite is central to both photomechanical operation settings, such as laser ablation monitoring at soft tissues, for instance. The focused energy discharged depends on the optical properties that may be altered during the reaction. Coagulation or carbonization may result in mode-specific thermal impacts, dental soft tissue vaporization, bleeding, or thermal osteonecrosis. Also, special touches, such as emission energy or laser irradiance, are not desirable. The laser color of light energy of the tissue influences the absorption and scattering phenomena to get signals that should be based on the charge pumped in the laser diode. Absorption provides the bioessence of the optical tissue for the therapeutic target; scattering could be used as a side product for diagnostic purposes.

1.2. Applications of Laser Technology in Dentistry

Lasers are utilized in numerous dental applications such as cavity preparation, caries removal, etching for restorative dentistry, soft tissue surgery, disinfection of root canals, teeth whitening and restoration, and phototherapy for pain relief. Additionally, they can be employed in the treatment of oral diseases, temporomandibular disorders, snoring, surgical wound decontamination, and mucositis. The advantages of using lasers are greater precision, minimal to no bleeding, reduced postoperative pain, less swelling, less inflammation, and faster wound healing when compared with using conventional surgical techniques. Several lasers could treat oral tissues, and they include carbon dioxide laser, neodymium-yttrium aluminum garnet laser, erbium-doped yttrium aluminum garnet lasers, diode laser, erbium, chromium: yttrium scandium gallium garnet laser, and helium-neon laser. (Tzanakakis et al.2021)(Maheshwari et al.2020)(Pandarathodiyil & Anil, 2020)(Convissar, 2022)(Chertov et al.2024)(Parker et al.2020)(Rajan and Muhammad2021)

Erbium lasers were found to be more indicative for cavity preparation, whereas neodymium-yttrium aluminum garnet was determined to be better for coagulating and ablating soft tissues due to the depth of penetration with these wavelengths. This shows the increasing popularity among dental practitioners to utilize lasers in their daily practice. The following case studies show the experts' experiences that depict the applications of laser systems and treatment procedures beyond those regarded within educational or working purposes. Periodontists utilize diode lasers for difficult-to-access pockets. Such current trends raise the necessity of more precise scientific foundations and new techniques in dentistry. These recent advances in laser physics provide more controllable dental treatments. Patients are more comfortable and heal faster than with traditional methods. The use of these techniques in general dental practice is no longer a futuristic dream. (Uslu et al., 2024)(Shakya et al.2023)

2. Overview of Dentistry in Saudi Arabia

2.1. Dentistry Practice in Saudi Arabia

Dentistry can provide a continuous oral health service to the public and involves patient care. A study showed that the oral health status in Saudi Arabia falls below the satisfactory level; more than 90% prevalence, and 53% of 12 to 15-year-old children suffer from caries. On the other hand, dental caries and periodontal disease are still major treatable oral health issues for the adult population of Saudi Arabia. These problems lead to major harm in the quality of life in Saudi Arabia and constitute a principal public health problem. The Kingdom of Saudi Arabia delivers publicly funded dental healthcare through a national publicly run dental service. The dental practice landscape in Saudi Arabia is a mix of governmental and private sectors. The government practice involves prevention, fillings, and minor extractions, covering free-of-charge treatment across the country. The private sector focuses on implants, cosmetics, complicated cases, veneers, fillings, and advanced procedures and therapies. The dental clinic in Saudi Arabia is structured as a primary care dental clinic in a hospital, where it is administratively under the umbrella of the Ministry of Health in various regions throughout the country. (Gowdar et al.2021)(Al et al.2021)(Al-Qahtani et al.2020)(AlGhamdi et al.2020)(Allam et al.2020)(Alshahrani et al., 2021)(Alkhaldi et al.2021)(Thomas et al.2020)

There are multiple challenges in the dental services in Saudi Arabia, including an increase in population and workloads, efficiency and waiting times, continuous patient flow with peak times, multiple booking systems, complex clinical pathways, health infrastructure that has rather remained the same for some years, resources, skills mix, and administrative difficulties, as well as concerns regarding training and recruitment of staff. While the patient population has grown, the demand for modern dental technologies has also increased, and individuals desire to have access to new technology in dental equipment. Laser-assisted improvements in diagnosis, prevention, and intervention in oral health diseases or conditions hold promise for significant positive effects. Lasers in the dental field have largely focused on surgical interventions, proposing more effective, less painful, and less adverse technological impacts on patient time and experience. In Saudi Arabia, implementing the system could be a formidable challenge as society acquires many renowned dental practitioners to adapt their knowledge and skills to new ways and different modalities in dental courses, both on and off the job. Educational providers must be made aware of the benefits of adequate training for individuals and of integrating the use of current-generation dental technologies at both practical and theoretical levels. The effective supply and quality of dental practitioners are challenges that might shape the future development of advanced dental practice. (Alfaraj et al.2021)(Sahab et al., 2022)(Orfali & Aldossary, 2020)(Al Agili & Farsi, 2020)(Meisha et al., 2021)(Alshihri et al.2021)(Chaudhary et al.2022)

2.1. Dental Healthcare System in Saudi Arabia

Saudi Arabia continues to restructure and reshape its healthcare system to accommodate the country's rapid population growth and demographic changes. In terms of oral healthcare, one million children aged 6-12 suffer from tooth decay, while 75% of both school children and adults have gum disease. Oral cancer is widespread among young adults, resulting in high treatment costs, while pediatric oral surgeries in university hospital settings are considered to be most common in the western region. Structure and Operation: Although mixed systems between government and private have been in place in Western countries, health services were provided in a completely government or non-governmental health system until the 1980s in Saudi Arabia. However, in 1960, healthcare services were provided in private clinics by physicians or individuals who had completed medical school or passed the dentist examination. As a result of expatriate migration, the Saudi government has focused on the provision of basic public health services, with dentistry divided between public and private. However, the absolute proportion of government-paid dental care in favor of patient-dentist experience, as perceived using simple discharge data, may help to be sacrificed in most societies in Saudi Arabia and avoid possible oral and dental diseases. Laws and regulations have been added to the operations of the KSA dental and medical profession, such as examining the Saudi Commission and obtaining a certificate to practice dentistry. Saudi universities, for their part, have tried to establish dentistry schools and training centers at all levels with an increasing number of graduates, training programs, and epidemiology studies in partnership with the ongoing regulatory bodies. Oral Health Promotion: The public health system offers education about the causes of tooth decay and gum disease, tooth care, and the role of diet in oral health. Sadly, the unit has never been very successful as an activity due to cost, workforce shortage, and enormous workload demands. Other activities, like those for children at schools, are performed by small NGOs to address and promote the prevention of oral diseases in children. Many cultural factors, practices, and lack of dental workforce also contribute to dental issues and the growing numbers of untreated caries, especially in children, poor adults, and a separate group of patients who are responsible for dental care. Early treatment is primarily practiced within the Middle Eastern context of families concerned with their oral health, especially regarding dental products. However, in the current situation, whether there is fear of dentists themselves or cultural indications about dentists, problems with cosmetic dentistry and laser applications are part of our experience. (Daghriri, 2022)(Sabbagh & Abudawood, 2024)(AlGhamdi et al.2020)(Alkhaldi, 2024)

2.2. Adoption of Laser Technology in Saudi Arabian Dentistry

Saudi dentists have been skeptical of the effectiveness and benefits of incorporating lasers into their practice. This claim has been supported by investigating the status of laser utilization in operations among a sample of dental practitioners throughout the kingdom. A set of probable reasons includes the following: first, dentists may perceive that lasers are somewhat inadequate, which reflects a lack of proper training and/or guidance. Second, it could be that some of them do not regard laser technology as a good investment due to the large initial financial potential those devices demand. The results of this study agree with this claim. Third, despite the investment in time and effort, some dentists may be facing patient indifference, which really makes this technology less appealing. This is also in line with this survey, since only 9% of the respondents prefer laser-assisted treatment. Finally, dentists worldwide are claiming that in developing countries, particularly in certain geographic regions, failure to supply necessary translation tools and/or training materials can be one of the barriers to adopting laser therapy. There are several future trends in Saudi Arabia that are worth discussing. We know the potential for a greater number of local dental clinics to incorporate laser technology has been laid. Moreover, educated consumers or successfully implemented laser devices drive some up-to-date clinics to incorporate new technology into their practice. (Ashifa et al.2024)(Alsulaimani et al.2023)(Al-Aali et al.2023)(Fattouh et al.)

Although almost half of the dental practitioners practicing in the KSA claim that they currently do not use lasers, it should be mentioned that a promising perspective has been observed in up-to-date clinics, whereby they have long been using dental laser technology in their practice. It should be noted that the top 5 dentists out of 92 that recorded the highest activity make up 45% of the summary percentage. This figure leads directly to the premise of potential doubling of those clinics' percentages upon meeting future optimistic perspectives, given the competitive dominance that they represent in the closure of the post-COVID era. Additionally, numerous second-generation dentists have established their new dental clinics at a more sophisticated level than that of previous clinics. To establish the strategic advantage, dental service provision does, however, take advantage of the latest health technology around the globe. This represents a different reflection on the bright future of the dental sector, whereby the expansion of medical service in laser dentistry will most probably spread at the domestic, as an updated customer side, and international levels as being included in the preferences of a mass of patients, dental tourists, and other people. As for dental practitioners presently using laser instruments in their clinics, it was highlighted by a surgeon that they do so because they are convinced of reduced postoperative healing damage, following lower connective tissue aggression, making laser dental surgery a feasible alternative or a better treatment option to use on pediatric, adult, and anxious patients, who tend to opt for sedation and general anesthesia. (Al et al.2021)(Helmi, 2023)(Nassani et al.2021)(Alkahtani et al.2021)(Alqahtani et al.2021)

3. Current Trends in Laser-Tissue Interaction Physics in Dentistry

Laser technologies have been evolving to offer more precise interactions with tissue for dental therapy. These evolutions are intended to deliver more comfort and rapid healing to patients. As technology has advanced, so too has the evolution of new applications using advanced laser-tissue interaction physics in dentistry. Clinical practice guidelines have incorporated possible future use of low- and high-energy laser therapy in various specialties of dentistry, as well as a potential scenario where such techniques can improve the social, economic, and health challenges associated with poor dental healthcare. Examining the current status of laser-tissue interaction development in Saudi Arabia makes the guidelines more focused, looking forward to demonstrating a novel collaborative audit in this sector between the top five universities in Saudi Arabia. (Rajan and Muhammad2021)(Coluzzi et al.2021)(Quazi et al.2021)(Fattouh et al.)(Sadiq et al.2022)(Al-Bakaa et al.2022)

Short-term research is still ongoing to discover ways that special designs in laser systems and innovative laser-tissue interaction techniques can improve the outcomes and performance of teeth therapy. However, the newest scientific philosophy has demonstrated how improving laser therapies is gearing towards a brighter effect on patient care. As such, the idea of intentionally decreasing the efficiency of the tissue laser interaction in a therapeutic process can introduce a novel concept of causing a controlled side effect to the thrilling effect on the local and overall patient health side of the therapy using lasers. Commercially, few products have managed to enter advanced applied research and are either commercially available or still under beta testing worldwide. Therefore, this report does not limit its scope to the novel and most commercially available techniques in the market. Hence, it aims to track modern research trials and advanced studies to cluster all 'cutting edge' research, applications, and designs of laser-tissue interaction. I have grouped all promising clinical trials and major literature reviews that have been exclusively published about modern laser-tissue interaction in dentistry, as well as novel treatment, therapy, or multi-discipline designs for dentally related therapy strategies using the laser.

3.1. Advancements in Laser Technology

During recent years, much advancement has been seen in core laser technology. A variety of lasers are used for several applications in the field of dentistry, such as Helium Neon, Excimer, Erbium:YAG, Nd:YAG, and CO2. However, the diode laser has been of particular interest as it allows photoactivated drugs for periodontitis and peri-implantitis. One of the greatest advancements in dentistry is with diode lasers. Lasers, such as neodymium-doped yttrium aluminum garnet, have a tremendous coagulation ability, very low infection rates, and enhanced handling ability in the soft tissues of the oral cavity. Nd:YAG, CO2, and

Er:YAG lasers hold a very low potential for aerosol formation while working on soft tissue, and therefore they may be less infectious. The Er:YAG laser has good handling and can cut through a tooth without causing any thermal damage up to a specific energy. (Reynolds et al.2020)(Arias-Herrera et al., 2024)(Schweigert et al.2024)(Dragana et al.2023)(Afrasiabi et al.2022)(Choe et al.2021)(Radunović et al.2020)

Lasers are available with a user-friendly interface, the ability to produce sound and light energy, and provide benefits for both the clinician and patient. Laser light can diagnose caries before cavitation occurs via laser-induced fluorescence. The introduction of carbon dioxide lasers kindled interest in pain therapy and curing dental problems with lasers, yet commercial use for dental procedures did not develop. Past research has shown that carbon dioxide lasers can be used alone in healing teeth during embryonic stages. Carbon dioxide lasers are effective in minor surgical procedures, which involve incisions, excisions, hemostasis, routine tissue reduction, oral papillectomies, treating aphthous ulcers, and fibroma removals. Nd:YAG lasers can provide vitality launch and have been used in dental resorption situations and osseous surgical exposure. Diode units are presently offered with increased power and capabilities and can operate at wavelengths and power levels that cause hard tissue ablation. However, there is still a need for affordable, inexpensive training for dentists in order to adapt to recent trends. (Chelkar & Raza)(Kamar et al.2020)(Al-Ani et al.2023)(Prado)(Parker et al.2020)(Gill et al., 2021)(Jnaid et al.2021)

3.2. Emerging Techniques and Applications

Emerging Techniques: Traditionally, dental lasers have been used in tissue management, including periodontal and cosmetic procedures, and as complementary materials in the treatment of hypersensitivity lesions. Early techniques and treatments of dental lasers involved soft tissue-based methods, such as those for implantology and prosthetics. Dental caries are treated effectively with lasers, although it has recently been shown that the cutting was non-selective in some types of treatment. Apart from that, discussions on current trends, such as non-invasive pain management during laser surgery in the head and neck and the use of carbon dioxide lasers as alternative sedation for pediatric dentistry, were also addressed under emerging techniques. A case study has shown a visible, aesthetic, and tangible result from the use of the Er:YAG laser for crown lighting. Biological and engineering laser work go hand in hand as new applications of dental lasers are adopted across various fields of dentistry.

Recent studies have shown new techniques that could be used with lasers, indicating a move towards less invasiveness. For example, the use of photobiomodulation as an alternative for trigeminal nerve pain management has been explored. Another study showed that low-level laser therapy could also be used for bruxism, which is one of the most popular indications for prescribing occlusal splints. Additionally, it has been tested whether the laser-assisted new attachment procedure, with or without enamel matrix derivative, could affect the reattachment of the periodontium to the root surface, which is an important goal and therapy in periodontology today. A recent review shed light on different types of lasers that could be applied to dental tissue, showing a wide variety of creations and applications of dental lasers.

4. Challenges and Limitations in Implementing Laser Technology in Saudi Arabian Dentistry

Aside from the deterring effect on potential development of laser research and use in dentistry, several challenges and limitations for introducing and using laser technology in Saudi Arabian dental practice remain, including the development of updated medical legislation and safety standards that also necessitate the protection of both dentists and dental patients. Additionally, future research and meetings should focus on the ethical use of lasers. In particular, the use of lasers within dental clinical practice has to be underpinned by a robust evidence base and ethical policy developments in order to protect the interests and privacy of patients. The potentially significant costs involved in procuring and maintaining professional dental laser systems represent a further barrier to the implementation of this technology within dentistry. This may be particularly problematic given the apparent rate of obsolescence of some laser devices. An absence of well-established and consistent practices based on solid scientific evidence to support or refute clear effects may also contribute to a lack of demand for dental laser treatments. This lack of well-established practices is compounded by the lack of interest and consensus about the use of dental lasers within the educational systems of Saudi Arabia to prepare dentists for clinical practice. This review discusses current trends in laser research and provides an overview of the existing and potential uses of laser technologies in dentistry. Additionally, it reviews the challenges and limitations that impede the integration of laser technology in dental practices. It concludes with suggestions for mitigation strategies that can be adopted in future laser-dentistry research in Saudi Arabia.

4.1. Regulatory and Ethical Considerations

Use of lasers in dentistry is regulated by the regulations published by the Ministry of Health, Saudi Arabia, initially in 2012 and re-issued in 2016. The regulations govern the general safety requirements and considerations as well as specific considerations concerning the operation, maintenance, and safety measures regarding laser technology. Ethically, two main issues must be considered when talking about laser therapy in dentistry. First, the principle of respect for autonomy, which is primarily based on informed consent; and, second, the principle of non-maleficence, which is related to the issue of the safety and efficacy of the therapy. Most institutions are covered under research, treatment, and financial consent.

As a patient, one should be informed about the nature of the treatment and what is expected from that. The standard guidelines on informed consent for laser therapy include that the patient must be aware that the method or device can legally and accurately be identified as being experimental. If the laser has received approval for use, it can be marketed and used in interstate commerce. However, even after approval, it can be utilized for applications and indications that have not yet been classified. If the use of a laser has been approved, a statement should be included that outlines the best-known treatment outcomes. Professional organizations concerned with laser therapy have emphasized the importance of a comprehensive education program covering not only hands-on training in methods but basic principles, safety, and a set of fundamental and advanced training programs including a supervisory program in the clinical setting. The over-marketing of laser treatments without solid evidence, respect for the standards, and informed consent represents unethical practices in the medical profession. However, a brief marketing announcement that informs the public of the availability of laser therapy as an option is in accordance with these guidelines. In short, informed consent can be stated in a simplified form as receiving 'sufficiently comprehensive information when seeking informed consent from patients' for medical treatments. We do hope that this will attract the interest of two groups such as stakeholders and those who are interested in the understanding of the ethical aspects of the presently available and latest versions of laser and its clinical employment from the information included in this review. This chapter will enhance the induction of ongoing dialogue between the stakeholders including laser professionals, ethicists, researchers, patients, healthcare specialists, and professional organizations regarding the recent developments in this regenerative method. We authorize high-tech companies and healthcare-related industries to utilize the information provided in this chapter for producing highly effective laser systems. The final judgment concerning the use of any excavating laser system will lie with the device operator, who should assume complete responsibility.

4.2. Cost and Accessibility

The high initial investment costs associated with laser technology have deterred many dental practitioners from adopting it in their practices. As of now, dentists seeking to offer laser treatments must attend expensive training courses and often rely on extensive travel to do so. The technology is largely inaccessible to rural clinics where laser technology and practitioners trained in its use cannot be supported by the surrounding market. Various economic models based on publicly funded laser technology centers, subsidized clinics, and others have been proposed to make lasers more accessible to practitioners. It is also important to note that the increased cost of laser-based treatment for the patient represents an economic barrier to treatment accessibility that must be taken into consideration. While laser therapy can be considered cost-effective in the long term, there are very few insurance schemes that may cover laser-based treatments in other countries, but non-publicly funded health systems, which is also the case in Saudi Arabia.

A fundamental pillar of increasing laser technology accessibility in dentistry, and in Saudi Arabia, will be addressing the economic feasibility and accessibility concerns. The minimum investment required to obtain a filler-free dental laser machine may prove to be an initial barrier to many small practices and dentists. Funding mechanisms such as grants or microloans made available to help small practice owners meet this initial cost may be of interest. Above and beyond just accessibility, mechanisms to ensure small practice owners have equal access to these funding sources are also essential. Investigating collaboration with organizations that support small business owners and increased dental access may also help identify additional support options for small practice owners.

5. Future Directions and Innovations in Laser-Tissue Interaction Physics in Dentistry

Laser-tissue interaction has played an important role in the physical aspects of dentistry. This text pushes the boundary and explores what laser-tissue interaction physics in dentistry could be like in the next 10 years. In particular, it has explored the future direction and potential new innovations in laser-tissue interaction physics perspectives. Integration of cutting-edge trends, strategies, and techniques that are currently advancing, as well as broad applicability to dentistry within the global context. This research has considered the impact of technology trends, strategies, and techniques that will shape this field, including artificial intelligence and machine learning, a diverse range of laser physics, innovative biomaterials, and nanotechnology. Currently, it is possible to use machine learning to create a smart laser application that helps to maximize effectiveness in dentistry and reduce negative complications when lasers are processed under treatment.

Laser application in modern dentistry is developing, striving to be more effective, more efficient, safer, faster, and painless. In the future, scientific knowledge needs to prepare an innovative way to effectively and safely use advances in the biophysics of laser-tissue interaction in modern dentistry. Furthermore, dentistry will be integrated into stronger collaborations, such as oral medicine, maxillofacial surgery, and cancer research, which can be used to develop a new, safer, and more effective early-detection technique. In order to keep up-to-date and fit with upcoming developments in laser physical interactions, proactive research strategies and technologies need to be investigated. This research will generally demonstrate some future directions, technological advances, and possible investigation prospects of laser-tissue interaction physics according to reasonable levels of view. This text demonstrates potential research as well as exploration initiatives that laser engineering research is to be conducted in dentistry.

5.1. Potential Impact of Artificial Intelligence and Machine Learning

In the future, artificial intelligence (AI), particularly deep learning and machine learning, may have a significant impact on various aspects of dentistry, primarily the LTI aspect. For instance, deep learning models can be implemented for diagnostic purposes, intelligent interpretation, and analysis of multidimensional data, which may improve treatment outcomes. Furthermore, intelligent analysis models may aid the clinician in suggesting personalized treatment protocols in addition to quantifying treatment outcomes, which has direct relevance to LTI modeling where variable patient-related factors may render the outcomes unpredictable. In the LTI field itself, the integration of deep learning and machine learning models may enable the prediction of treatment responses based on patient-related data, rendering LPC as an alternative for analysis. From an experimental and technological perspective, incorporating real-time visual feedback in closed loops, intelligent control systems, and dental materials with embedded optical feedback systems can be developed. (Taraji, 2022)(Kung et al.2023)(Köktürk et al.2024)(Diaby et al.2023)(Kung, 2023)

Surprisingly, few researchers have investigated these propositions in dentistry and laser dentistry, particularly in Saudi Arabia. Machine learning algorithms have been utilized to analyze the complex outputs following clinical procedures and predict outcomes based on patient and operative factors, which can be utilized in further comparative LTI studies and provide significant implications for treatments. The integration of the prediction results with the physical simulation platforms provides the ability to create newer virtual learning, augmented reality, or virtual reality training platforms for dental surgeons. In the clinic, the real-time feedback systems may improve patient satisfaction and efficiency. Although these suggestions are futuristic to some extent and need innovative transdisciplinary collaboration, they hold substantial potential to change the landscape of current dentistry practice.

5.2. Nanotechnology and Biomaterial Integration

Nanotechnology is an interdisciplinary science that began in the late 1950s when people first found that the properties of a material can change when changing its size. This process can be used in the field of medical technology and can also be implemented in the field of treating diseases. Because of this, research has been conducted to utilize nanomaterials in the human body. This trend of integrating nanotechnology and biomaterials might open doors to a new era in the idea of regenerative dentistry. There is increasing interest in integrating nanomaterials with the overall formulations of dental materials. This trend is also having a positive impact on the regenerative capabilities of dental implants, and this research area promises an innovative future for dental implants in the form of antimicrobial, anti-inflammatory, angiogenic, and stimulatory properties. (Asmatulu et al.2022)(Saweres-Argüelles et al.2023)(Cheng et al., 2021)(Damokhi et al.2022)(Malik et al., 2023)(Wibowo et al.2024)(Sathish et al.2024)(Abaszadeh et al.2023)

Transformative research on oral dental implants using nanotechnology is currently being conducted, and research reports and ongoing clinical trials are evident in the field. This indeed reflects the potential of nanotechnology to be used as an implant coating technology. Similarly, in one of the more sophisticated applications, biomaterials developed in response to targeted therapy have ethical, legal, and social implications. One of the most noteworthy recent innovations in the field of biomaterials is the development of traceable drug delivery via encryption in biomaterial systems. These find intensive applications in load-bearing tissue engineering scaffolds, anti-inflammatory dressings, and as a unique advancement in personalized medicine. However, the results must be confirmed by ongoing clinical trial data, and there is a call for close collaboration between basic and applied scientists in the areas of materials science, nanotechnology, and dentistry to promote future practices. The potential significance of this research is to develop personalized prosthetic dentistry to design a biomaterial device to interact with a laser. Once this new trend is explored, this laboratory research may allow us to further develop biointegration prostheses to refine the choice of biomaterials based on a given patient's characteristics and health status as well as their rate of new bone formation. (Dakhale et al., 2023)(Dipalma et al.2024)(Accioni et al.2022)(Marasli et al., 2024)(Sen et al.)

The potential of nanoscience and nanotechnology for medicine has generated augmented growth and research interest. Convergence science features cross-sector research involving chemists, biologists, materials scientists, and physicists. This interdisciplinary endeavor has disrupted several conventional beliefs and ways of doing research. In modern drug delivery systems, these findings have led to the development of revolutionary nanoparticles with a high range of therapeutic goods, including drugs, gene delivery materials, and contrast agents. Additionally, targeted delivery can be accomplished by functionalizing these particles, therefore increasing the effectiveness of treatment. Laser tissue interactions may also potentially benefit from the integration of advanced biomaterials on many frontiers. In general, a model designed for tissue photothermolysis may lead to enhanced phototherapeutic success outcomes when paired with a vehicle designed to carry a therapeutic that enhances a specific mechanism of cellular destruction. Therefore, in the field of photomedicine, the combination of devices engineered to interact with specific laser treatments and enhanced integration of biomaterials into these medical systems is tantalizing and innovative. Furthermore, the combination of these disciplines can lead dentistry to revolutionize personalized macromolecular prosthetic development. (Amna et al.2022)(El-Naggar et al.2024)(Ashraf et al.2021)(Ahire et al.2022)(Yadav et al., 2023)

6. Research and Development Initiatives in Saudi Arabia

In the Kingdom of Saudi Arabia, scientific research and development activities are rapidly increasing. In 2008, the Saudi government spent $5.54 million on research and development initiatives. This is equivalent to 0.04% of the national GDP. Consequently, investment in research and development has a major impact on new product and instrument development. For laser technology in dentistry to be used effectively, investing in scientific research is essential. The personnel and necessary infrastructure for in-depth fundamental discoveries are available through Saudi universities or research institutions.

Extensions of the present work should involve full-scale collaborative interdisciplinary research projects between universities, dental institutions, and industrial partners to use available resources wisely and to uncover the hidden intellectual wealth in the Kingdom. A suitable research initiative support program is sponsored by a local organization. This organization supports research in various fields, including laser technologies, through its different funding programs. One of these is a program established to stimulate the establishment of an innovation-driven knowledge economy in the Kingdom of Saudi Arabia. In the dental sector, research on high-impact topics related to tools and applications in laser use has recently been conducted in the Kingdom. Additionally, case studies were shared that showed local researchers' capacity to develop dentistry lasers. Promising initiatives are being pursued at a research center, which is the most open laser research institution in Saudi Arabia, as well as a laser research laboratory and other research centers. These centers foster scientific research and education aimed at fulfilling their mission as respected producers and disseminators of expertise in health and laser physics. (Chen et al.2020)(Baca et al.2023)(Boboc et al.2022)

6.1. Collaborative Projects and Funding Opportunities

In order to transform current dental laser technology and research in Saudi Arabia, various partnerships have been formed among the academic sector, the private sector, and the governmental sector to produce meaningful combined efforts. Given that lasers can be used for various biomedical applications, more specifically in the field of periodontology and oral surgery, dental laser research is considered a multidisciplinary field, and thus, having different partners including governmental, private, and academic institutions is essential. Furthermore, in order to have deeper research with broader applications in dentistry, it is recommended to collaborate on different levels, including but not limited to dentistry, engineering, medicine, lab or animal studies, and others.

The availability of financial resources is considered a very important factor that can direct, plan, and govern newly emerging research programs. Financial resources are mainly from governmental grants, institutes, or private sectors. In Saudi Arabia, for example, there are initiatives that allocate a budget to support innovative projects that address the main issues highlighted in their calls for proposals. An example of this kind of collaboration in dentistry has resulted in four successful projects. Furthermore, there are also research chairs, which are funded by governmental resources, in addition to other scientific research centers or institutes. Another interesting and well-known resource for funding any research project in Saudi Arabia is entering into research collaboration and partnerships with Saudi industry. An example of such research in dentistry is the collaborative projects of lasers in dentistry.

6.2. Key Research Institutions

Saudi Arabia has seven universities that offer education in laser technologies in dentistry and a single center that offers postgraduate training. King Saud University, Alfaisal University, Riyadh Elm University, and Najran University are highly engaged in the area of laser applications in dentistry, either by offering updated courses or by conducting cutting-edge research in their specialized centers focused on minimally invasive medicine. Additionally, the Prince Sultan Military Medical City in Riyadh offers laser training and workshops for specialists and residents. King Khaled Eye Specialist Hospital in Riyadh and Qassim University offer courses in laser science but not for oral and dental applications. King Saud University, Riyadh Elm University, Alfaisal University, and Prince Sultan Specialized

Orthopedic Hospital in Riyadh have established specialized research centers aimed at furthering the concept of integrated minimally invasive medicine. These centers offer workshops to transfer their knowledge to the greater community. The centers also commonly host mini-conferences in regions of the kingdom to promote the culture of minimal and non-invasive dentistry. Alfaisal University and Prince Sultan Specialized Orthopedic Hospital in Riyadh invite guest speakers from outside to enrich the knowledge and experience of their audience.

There are collaboration initiatives between research institutions and stakeholders in the dental industry to develop laser equipment that is efficient, easy to use, and safe in clinical practice. Dentists need equipment that can be quickly adjusted and have uniform power outputs to reduce treatment duration. Feature-rich electronic lasers allow the clinician to enter the desired reduced output power for various tasks. The dental companies need commissions for marketing and distributing top-quality dental laser products from trusted and certified research centers. National and international study protocols are being conducted jointly between King Saud University’s College of Dentistry and Eastern Dentists’ Specialized Hospital. The use of diode lasers for different applications is considered to be a hot topic in dentistry to combine highly aesthetic materials and the healing properties of low-level lasers. Current and ongoing research with many applications of lasers is running at King Saud University, the largest in the country and one of the top ten in the Arab region. The integration of six types of lasers with platelet-rich fibrin is now a major project. Relevant to research proposals, animal trials have been successful. This research has the strong potential to build a new concept of immediate implant loading. With the solid experience in the Knowledge Transfer Project and the initial approval of King Saud University, collaboration with the laser company will observe how the soft-tissue reactions and the quality and quantity of bone will be affected using the three diode lasers when integrating them in the oral surgery field, funded by the industry.

7. Conclusion and Recommendations

To conclude, the laser-tissue interaction is the fundamental principle in any dental laser application. The knowledge of this principle is essential for the appropriate use of the laser. Continuous work has been carried out in developing laser technologies and finding possible applications. To encourage the use of lasers in dental applications in Saudi Arabia, further studies in this area can be conducted. The limitations, recommendations, and some future research directions for laser-tissue interaction in dentistry are hereby provided. In conclusion, the development of dental lasers in Saudi Arabia has faced multiple challenges. These include financial and infrastructural burdens during the phase of purchase and maintenance of the equipment. As the sine qua non, further training and knowledge on the interaction of the laser are required for suitable use and safe practice in the clinics. Not only clinical applications are to be indicated as future directions, but it is necessary from the basic level to consider the development of various modern techniques and the use of nanotechnology, artificial intelligence, and machine learning for further progress. Laser features, including wavelength sensitivity, irradiation directions, tissue color, color illumination, phototherapy, or even nanotechnology, can be part of future research on the interaction of the laser irrespective of skin type, age, and skin tone. By adapting the above into the educational curriculum of healthcare professionals, these advancements in science can lead to success and provide safe practices that set a benchmark for developing creative and proactive applications based on new principles. In Saudi Arabia, only the Carbon Dioxide laser has been developed for use in several medical and surgical fields.

7.1. Summary of Key Findings

Our review has shown the main trends of scientific research based on the interaction between lasers and tissue in dentistry and oral-facial surgery. In this context, investigating the potential of laser applications for dental and oral diseases and the most studied interests in scientific research revealed prospects for new investigations. It comes to light that more recent research has focused on newer technologies and their applications in medicine and dentistry. However, certain methods remain elusive and provide insight for future research. Additionally, the investigation has revealed significant barriers to overcome in the dissemination of such innovations in general in

Saudi Arabia and specifically in dentistry in advanced countries. These challenges encompass multiple aspects, such as the regulatory framework, the high cost, and the need for further research in the field, necessitating a corresponding expansion of the training and education available.

In Saudi Arabia, it has been shown previously that, although the first laser in medicine and dentistry was used in 1960, severe restrictions existed related to its use, which was only licensed for government hospitals. Medical equipment purchases needed substantial government approval at the hospital level. However, dental manufacturers' salespeople have previously sold products directly to dentists in private clinics, with the approval system simplified for small pieces of medical equipment. In addition to advances, the trajectory in which the research is moving is not only technologically advanced treatments but also more research to develop the methods themselves. However, the general consensus on 'traditional' lasers is a future reframing of how dental research can be conducted, as they offer several practicalities compared to current technology. More key themes that emerged are summarized in the following points.

7.2. Recommendations for Future Research and Practice

1. Increased research funding. The researchers should dedicate extra efforts to acquire funds for the integration of new approaches in various therapies and to suggest new approaches that might improve the current practice.

2. Strengthen educational programs in dentistry. The skills and knowledge of the staff to use lasers should be enhanced through incorporating comprehensive programs about laser technologies in the curricula of dental schools, facilitating hands-on training in undergraduate integrated courses. It is recommended to create collaboration between dental colleges and educational institutions using standard aids, including animal and human pathology to master the operational mechanism of these technologies. Provisions should be made for theoretical and hands-on training during postgraduate residency curricula, in addition to continuous educational workshops designed for professionals in the field of laser dentistry.

3. Development of new guidelines and regulations in dentistry. It is advisable to provide required references and to perform new research studies to confirm new guidelines and regulations regarding the use of lasers and other new mental health services. This will provide new legal guidelines to use systems with different capacities and technologies. As the organization moves toward a process of digital development and improvement of systems in dentistry, policies related to the AI field must be put in place. As such, strategies should be developed to regulate the clinical use of AI to prevent future problems from occurring with this technology. It is expected that the use of AI and nanotechnology will open new avenues in the fields of dentistry in general and microscopic surgery in particular. Adjustments or updates related to AI services and nanotechnologies used in clinical dental applications should be understood from both a legal and ethical perspective. Like other clinical instruments used in dentistry, optimal practices and technology usage manuals must be available. Standard operating procedures should be followed before, during, and after installing these systems. Error reports and effective program feedback must be provided to strengthen future systems.

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