

# FEMTOSECOND LASERS IN DENTAL MEDICINE: APPLICATIONS AND ENVIRONMENTAL BENEFITS

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## ABSTRACT

Like many other areas of medicine, dentistry faces challenges in terms of sustainability and reducing negative environmental impacts. Lasers, which have become an important tool in modern dental practise, offer numerous advantages in therapeutic procedures, but also open up opportunities to reduce energy consumption and medical waste. Femtosecond lasers represent a groundbreaking advance in dentistry as they offer unrivalled precision and efficiency thanks to their ultra-short pulse duration. This article deals with the basic operating principles of femtosecond laser technology and its numerous applications in modern dentistry. The focus is on clinical applications, including hard and soft tissue procedures, cavity preparation and endodontics, with an emphasis on improved outcomes and reduced discomfort for the patient. In addition, the study investigates the environmental benefits of the femtosecond laser, such as reducing material waste and eliminating the use of harmful chemicals. By integrating high performance technology and environmentally conscious practises, the femtosecond laser is positioned as a key component on the path to a more holistic and sustainable future of dentistry.

**Keywords:** *femtosecond lasers, dental medicine, environmental aspects, sustainability*

## INTRODUCTION

In today's world, it is essential to adopt environmentally friendly practises in all areas of life, including dentistry. Eco-friendly dentistry aims to reduce the environmental impact of dental practise through waste minimisation, energy conservation and the use of modern technologies. It promotes sustainability, protects the environment and benefits both patients and dentists [1]. Environmental sustainability is becoming

increasingly important in dentistry. Dentists should focus on prevention, reducing travel emissions and responsible use of materials to reduce the industry's environmental impact. Promoting sustainable practises not only protects the planet, but also improves the quality of dental care and supports a healthier future [2].

Technological progress in medicine and dentistry not only brings improvements in diagnostics and therapy, but also opportunities

to reduce negative environmental impacts. One technology that is becoming increasingly important is the use of lasers in numerous medical and dental procedures. In addition to the advantages in terms of precision and efficiency, lasers can contribute significantly to reducing waste, using fewer chemicals and working more energy-efficiently, which also makes them attractive from an environmental perspective. Conventional surgical instruments such as scalpels, scissors and other tools often need to be sterilised, replaced and disposed of after a limited number of uses, especially if they are disposable. In surgical and dental practises, this results in large quantities of medical waste that require special treatment due to the potential biohazard. Laser devices, on the other hand, can be used multiple times without the need to replace individual parts or generate waste after each use. Laser is an abbreviation for the term “Light Amplification by Stimulated Emission of Radiation” [3, 4]. In dentistry, lasers were first used as a substitute for mechanical cutting and drilling in the processing of hard tissue, e.g. for caries removal and cavity preparation. Today, lasers are widely used in dental practise [5, 6]. Since the 1970s, lasers have been used to treat infections in the oral cavity, and with the development of new technologies, their application has expanded to endodontics, periodontics, orthodontics and aesthetic procedures. Thanks to their versatility, simplicity and reliability, lasers represent an efficient alternative to traditional oral surgery. Their ability to stimulate cells at a biological level has contributed to their widespread use in dentistry [7].

Different types of lasers are used in dentistry due to their specific properties and applications. Diode lasers are mainly used for soft tissue treatments and bleaching, erbium lasers for hard and soft tissue, CO<sub>2</sub> lasers for soft tissue surgery and Nd:YAG (neodymium-doped yttrium aluminium garnet) lasers for periodontal therapy. Dentists select the appropriate laser depending on the requirements of the procedure [8].

## FEMTOSECOND LASER

A femtosecond laser is a pulsed laser that emits optical pulses with a duration in the femtosecond range ( $1 \text{ fs} = 10^{-15} \text{ s}$ ) and operates in the infrared range. It also belongs to the category of ultrafast lasers or ultrashort pulse lasers. Due to the enormous progress that lasers have made throughout history in generating shorter laser pulses, femtosecond lasers have become promising tools for medical applications. Ultra-short pulse lasers are widely used in medicine. Thanks to their extremely short pulse duration, they enable high energy and great precision [9 - 11]. In contrast to nanosecond lasers, femtosecond lasers do not cause such a large zone of thermal tissue damage due to the significant difference in the length of the laser pulse. While ionisation, sample heating and vapourisation occur during the laser pulse in laser ablation with nanosecond lasers, femtosecond laser pulses are so short that these phenomena only occur at the end or after the end of the laser pulse [12]. Femtosecond lasers can be used in dental and orthopaedic surgery, although they are currently largely limited to research, but have great potential for clinical applications. Femtosecond ablation is also being developed for endoscopic applications that allow precise analysis and removal of tissue in hard-to-reach areas of the body, e.g. for the detection of tumour margins and removal of malignant tissue [13].

Femtosecond pulses can be generated by different types of lasers, each with specific characteristics and uses:

- (i) Solid-state lasers (e.g. Ti:sapphire) generate high-quality ultrashort pulses (up to 5 fs) with high average power and repetition rates between 50 and 500 MHz,
- (ii) Fibre lasers typically offer 50 - 500 fs pulses with moderate power and are compact and cost-effective, but technically complex due to non-linear effects,
- (iii) Dye lasers played a key role in generating ultrashort pulses ( $\approx 10 \text{ fs}$ ), but are now rarely used due to difficulties in handling and decomposition of dyes,

- (iv) Semiconductor lasers, including VECSELs (Vertical External Cavity Surface Emitting Lasers), can generate high repetition rates and femtosecond pulses, but usually with low pulse energies,
- (v) Frequency-converted sources use components such as optical parametric oscillators to extend femtosecond lasers to tunable wavelengths,
- (vi) Other types, such as free-electron lasers, can even generate femtosecond X-ray pulses.

Each type of laser serves different applications depending on pulse duration, energy, repetition rate and wavelength [10].

### Functional mechanism of the femtosecond laser

The wavelength of the laser, the pulse duration and the power per pulse can lead to different interactions with the irradiated medium due to plasma formation and ionisation processes [14]. Regarding the wavelength, Rapp et al. concluded that the maximum temperature increase under optimal conditions for infrared and green radiation was 5.5 °C, which is within the acceptable temperature increase limits for conventional dental treatments. Ultraviolet radiation, on the other hand, increased the internal temperature of the tooth considerably, far beyond the acceptable limits, and caused severe damage to the tooth structures. Therefore, the ultraviolet wavelength is not suitable for femtosecond ablation of teeth. Therefore, the wavelength for the treatment of hard tooth structures should be in the infrared (1030 nm) to green (515 nm) wavelength range [15].

The main difference between femtosecond laser ablation and ablation with picosecond or nanosecond lasers lies in the time scale of electron excitation, Figure 1. The duration of the femtosecond pulse is significantly shorter than the scattering time of electrons on photons (about 1 picosecond), which means that the femtosecond pulse ends before the electrons transfer their thermal energy to the

ions. This minimises thermal diffusion and restricts thermal damage to a limited area [14].

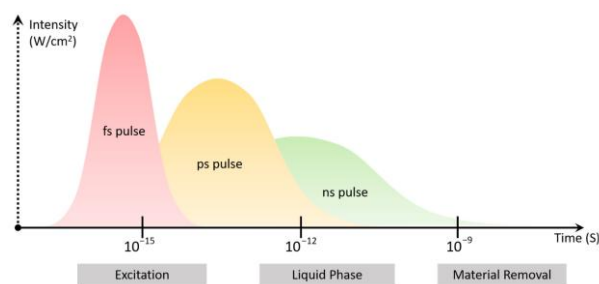


Figure 1. Schematic illustration of femtosecond, picosecond, and nanosecond laser pulses, showing time-intensity profiles and the main mechanisms of material removal [16]

Niemz et al. compared lasers with pulse durations in the millisecond, microsecond and nanosecond range with lasers with pulse durations in the picosecond and femtosecond range. It has been shown that lasers with pulse durations of milliseconds, microseconds and nanoseconds cause considerable heating when ablating hard dental tissue, whereby the thermal interaction mechanism dominates. In contrast, lasers with pulse durations of picoseconds and femtoseconds ablate the tissue by generating an ionisation plasma that prevents excessive heating of the surrounding tissue [17]. Therefore, the interaction of ultrashort laser pulses with the material is called thermally confined, which means that thermal diffusion takes place within the irradiated area itself. This property enables minimal thermal and mechanical damage to the surrounding tissue during laser imaging, drilling and ablation, making femtosecond lasers ideal tools for use in dentistry [18].

With ultrashort laser pulses, especially in the femtosecond range, pulses with extremely low energy in the milliwatt range can be generated, while at the same time extremely high peak powers of over terawatts per pulse can be achieved. In addition, the femtosecond pulse generates a sufficient number of free electrons through nonlinear ionisation, making femtosecond lasers particularly suitable for precise micromechanical applications, e.g. in dentistry and hard tissue processing [14]. Chen

et al. investigated the effects of laser fluence (energy density), scan line spacing and ablation depth on the efficiency of a femtosecond laser in the three-dimensional ablation of dental enamel and dentin and concluded that the ablation efficiency for enamel and dentin is maximised at different laser fluence values and scan line numbers, while it decreases with increasing fluence above the optimum value, with increasing scan line spacing beyond the laser spot diameter or with increasing ablation depth [19]. The key parameters of femtosecond lasers for dental applications include: wavelength, pulse duration, pulse energy/fluence and repetition rate. Wavelengths vary, but 1030 nm is common, with pulse durations typically in the 275 - 400 fs range. Pulse energy can be up to 400  $\mu$ J and repetition rates are often approximately 100 kHz [20 - 22]. Femtosecond lasers offer high-precision ablation of dental materials with minimal side effects, making them ideal tools for dental and other medical applications requiring precise microsurgery with controlled interaction with biological tissue [14].

## AIM AND RESEARCH STRATEGY

The aim of this paper is to present the use of lasers in dentistry, in particular femtosecond lasers, and their potential contribution to the sustainable development of dental practise. A comprehensive literature research was conducted to identify relevant studies related to the applications and environmental aspects of femtosecond laser technology in dental medicine. The electronic databases PubMed, Web of Science, Scopus, and Google Scholar were searched for studies published up to July 2025. The following combination of keywords and Boolean operators was used: (“femtosecond laser” OR “ultrashort pulse laser”) AND (“dentistry” OR “dental medicine” OR “dental applications”) AND (“environmental benefits” OR “sustainability” OR “eco-friendly dentistry” OR “green dentistry” OR “energy efficiency” OR “waste reduction”). Only peer-reviewed articles written in English were considered. Reference

lists of included articles were also manually searched to identify additional eligible studies.

The research question addressed in this review was: What are the current clinical applications and potential environmental benefits of femtosecond laser technology in dental medicine?

To ensure relevance and scientific validity, the inclusion and exclusion criteria were defined according to the *PICO* framework as follows:

*Patients/Population (P)*: Human subjects undergoing dental procedures in which femtosecond laser technology was applied.

*Intervention (I)*: Use of femtosecond laser systems in dental treatments (including hard and soft tissue procedures, surface modification, cavity preparation, pre-implantologic preparation, adhesion enhancement, and biomimetic remineralization).

*Comparison (C)*: Conventional dental techniques performed without femtosecond lasers or using other types of lasers (e.g., erbium, Nd:YAG, CO<sub>2</sub>).

*Outcomes (O)*: Clinical efficacy (precision, healing time, patient comfort, adhesion quality) and environmental impact indicators (reduction of material waste, energy efficiency, and minimization of harmful chemical use).

Studies were eligible for inclusion if they evaluated the application, advantages, or environmental aspects of femtosecond lasers in dentistry, either experimentally or clinically.

Studies not related to dental applications of femtosecond lasers, In vitro studies unrelated to clinical practice, reviews, editorials, commentaries, and conference abstracts, articles not written in English, studies without relevant information on environmental or clinical outcomes were excluded.

## APPLICATIONS OF FEMTOSECOND LASER IN DENTAL MEDICINE

### Teeth preparations

One of the most important advantages of femtosecond lasers is the possibility of precise temporal and spatial control of the temperature profile. When drilling dentin with femtosecond pulses, the pressure amplitude is 2 to 3 times lower compared to acoustic transients generated with nanosecond pulses. This factor plays a key role in crack prevention in the enamel, which could cause further carious lesions and jeopardise the success of the treatment [18]. The use of adequate laser power, minimal overlap of neighbouring ablation lines and precise focusing of the laser on the ablation plane are the key to achieving high ablation efficiency in cavity preparation on enamel and dentin with a femtosecond laser [19]. A repetition frequency of around 100 kHz (500 fs,  $\lambda = 1045$  nm) is recommended for the femtosecond laser, at which no thermal damage to dentin and enamel occurs. If femtosecond lasers are used exclusively for cavity preparation, the duration of the laser treatment should be kept below 1 minute, as the temperature then rises by 1.3 °C, which is physiologically acceptable and does not cause irreversible damage to the dental pulp [21]. Further advantages of the femtosecond laser are the absence of a residual layer, the disinfection of the dentin and enamel surface before filling and the shorter treatment time, which means a more comfortable procedure for the patient [23].

### Biomimetic remineralization

Biomimetic remineralisation is one of the best techniques in which damaged tooth tissue is minimally removed and then mineral deposition is stimulated to mimic the structure of a healthy tissue. To improve biomimetic remineralisation of dentin in the treatment of third-stage caries, when the caries has reached the dentin layer, photoactivation with a femtosecond laser with or without antimicrobial agents leads to remineralisation of the tooth structure. The degree of

remineralisation depends on a number of variables, including the wavelength of activation and the active ingredient used, if any. The best results were obtained with the remineralising agent *Moringa oleifera* when photoactivated with a femtosecond laser at 445 nm [24, 25].

### Surface modulation

The femtosecond laser can be used on the enamel surface to prevent the development of caries. The application of the femtosecond laser on the surface does not cause any significant morphological changes in the enamel, while at the molecular level it reduces the amount of free carbonate ions and thus reduces the risk of caries development [22, 26]. In addition to modulating the surface of dental hard tissue, femtosecond lasers are also used to modulate the surface of implants to improve their roughness and the surface itself for osseointegration and to enable a larger contact area with the bone [27, 28]. Laser treatment of implant surfaces aims to mimic the appearance of trabecular bone at the micro- and nanoscale. Further advantages of laser treatment of implant surfaces are the possibility to customise the design of the implant surface and to reduce the adhesion of biofilms and bacteria [29, 30].

### Increase of adhesion

Looking at the adhesion between two materials, surface modulation can increase the shear strength between the two materials. To increase the shear strength between zirconia and orthodontic metal brackets, a femtosecond laser with an average power of 200 mW and a width of pits and protrusions of 60  $\mu$ m is used. Conditioning of zirconia surfaces is performed before bonding metal brackets, as it ensures sufficient bond strength. In the shear strength between composite cements and zirconia, increasing the roughness of the zirconia did not increase the adhesion between the two materials. The increase in adhesion between the two materials is made possible by the distribution of cross-shaped depressions and

protrusions, which create areas of retention irregularities and increase the shear strength between the two materials. In order to improve the adhesion between composite cements and zirconium, a silane primer is also used, which enables a chemical bond between phosphorus, oxygen and zirconium (P–O–Zr) and thus improves the adhesion between resin and zirconium. The bond between composite resin and ZrO<sub>2</sub> (zirconium dioxide) is susceptible to hydrolytic degradation, regardless of the pre-treatment method [31, 32]. There is still no standardized protocol that includes the laser parameters (energy per pulse, repetition rate, pulse width and spot size) for an ideal surface treatment of zirconia to increase bond strength [28].

### **Pre-implatologic preparation**

In recent years, the use of lasers in implantology has been investigated to replace conventional drilling of bone cavities. Compared to conventional mechanical drilling, the use of optimised femtosecond laser pulses in the automated preparation of implant cavities has shown clear advantages in preserving the microstructure of the bone tissue. Laser-prepared cavities have smoother margins and better preservation of the microstructure, which is crucial for successful integration of the implant into the bone tissue and subsequent functional restoration. Other advantages of using lasers to prepare implant cavities include improved precision and safety as well as significantly less thermal damage to the surrounding tissue [33]. The effects of femtosecond laser ablation on the bone tissue depend on parameters such as scan rate and power output. Suboptimal parameters can increase cavity tapering, cause carbonisation and increase tissue temperature (5 - 100 °C). Since the cut is the result of overlapping multiple ablations at single points, a higher power and energy density increases the ablation rate and depth of cut. However, too much energy can be absorbed by the bone tissue and converted into heat, which can lead to carbonisation. Reducing the scan rate increases the number of pulses at a single point, which increases the ablation rate and

depth of cut [34]. Femtosecond laser ablation of cortical bone can also induce osteogenic differentiation of mesenchymal stem cells (BMSCs, Bone Marrow Mesenchymal Stromal Cells) and thus promote osseointegration of implants. The orientation and organisation of the differentiated cells depends on the distances between the laser-generated lines, with better orientation and organisation being observed at larger distances between the laser-generated grooves [35, 36].

### **THE ROLE OF FEMTOSECOND LASER TECHNOLOGY IN MODERN DENTISTRY: TOWARDS A HOLISTIC AND ENVIRONMENTALLY SUSTAINABLE APPROACH TO TOOTH PREPARATION**

Conventional tooth preparation methods, which primarily involve the use of high and low-speed rotary instruments in addition to manual tools, are clinically and ecologically questionable in several respects. Mechanically invasive methods are highly dependent on the experience of the operator and often lead to undesirable effects such as microcracks, thermal injury and the formation of a smear layer, all of which can compromise the integrity of the tooth and the effectiveness of the bond. In addition, conventional techniques usually cause discomfort to patients, who often require local anaesthesia, and can create psychological barriers to dental treatment.

From an occupational health perspective, repetitive use of vibrating rotary handpieces is associated with a high prevalence of musculoskeletal disorders in dentists, including hand-arm vibration syndrome (HAVS), carpal tunnel syndrome, osteoarthritis and reduced grip strength. These risks emphasise the need for more ergonomic and user-friendly alternatives.

In addition, the need for continuous water cooling during conventional reprocessing not only increases the complexity of the procedure but also contributes to environmental pollution through water and energy consumption and the

disposal of contaminated aerosol particles and residues.

In response to these clinical, ergonomic and environmental challenges, laser-based tooth preparation has established itself as a minimally invasive and environmentally friendly alternative. Laser systems offer precise tissue removal with low heat generation, minimal vibration and virtually no noise, which increases patient comfort and, in many cases, eliminates the need for local anaesthesia. Lasers also avoid the formation of a smear layer, which favours better adhesion and reduces the need for aggressive chemical cleaning agents.

By integrating laser technology into restorative protocols, dentistry is moving towards a more holistic model of care - that prioritises the well-being of the patient, the health of the dentist and the protection of the environment. This paradigm shift not only leads to better clinical outcomes, but is also in line with global efforts towards sustainable healthcare [20, 23, 37].

One of the main advantages of femtosecond lasers is their precision and non-thermal tissue ablation, which makes it possible to perform complex surgical procedures without

mechanical tools that often need to be replaced and sterilised. In ophthalmology (e.g. Laser-Assisted In Situ Keratomileusis procedures, LASIK), the femtosecond laser replaces the microkeratome - a blade that needs to be replaced regularly and generates waste. The same applies to dentistry, where the femtosecond laser enables cavity preparation without a drill, periodontal treatment without a scalpel and minimally invasive procedures without consumables.

In contrast to conventional methods, which use a large number of disposable instruments, the femtosecond laser uses optical fibres and light guidance systems that are reusable and last longer.

Replacing conventional surgical and dental instruments with femtosecond lasers therefore leads to a significant reduction in medical waste, which relieves the burden on waste disposal and contributes to environmental protection [15, 23, 38, 39]. Table 1 summarizes quantitative and qualitative differences between femtosecond lasers and conventional methods in dental procedures, emphasizing both environmental benefits (reduced waste) and clinical outcomes (precision, patient recovery).

Table 1. Comparison of femtosecond lasers and conventional methods in dentistry [20, 21, 40]

Parameter	Femtosecond laser	Conventional laser / Mechanical methods	Environmental / Clinical Benefit
Tissue ablation precision	High (sub-micron accuracy)	Moderate	Reduces collateral tissue damage, less need for corrective procedures
Postoperative pain	Lower	Higher	Faster recovery, fewer follow-up visits
Generation of solid waste	Low (optical tips, small e-waste)	Moderate-high (bur, drill bits, handpieces)	Less solid / medical waste produced
Liquid waste (irrigation/cooling)	Minimal	Moderate-high	Reduces wastewater generation
Thermal damage	Minimal	Higher	Reduces need for repair / replacement of damaged tissues
Laser plume / aerosol	Low volume, fine nanoparticles	Higher volume, larger particulates	Reduced exposure to harmful aerosols
Patient outcomes	Improved healing, fewer complications	Variable	Better clinical outcomes and satisfaction

Aggressive chemicals are often used in dental procedures, particularly in tooth whitening and the treatment of periodontal disease. Due to their exceptional precision, femtosecond lasers enable photomechanical and photochemical effects that replace or reduce the use of chemicals. Examples include tooth whitening, where femtosecond lasers can activate low-concentration gels faster and more efficiently than conventional methods, reducing the amount of chemicals used, and the treatment of periodontal disease, where photodynamics combined with femtosecond lasers enables selective destruction of pathogens without the use of antiseptics or antibiotics.

As femtosecond lasers do not generate any significant heat, the need for coolants and solvents that would otherwise be used during treatment is also reduced.

Although femtosecond lasers often provide environmental benefits through precision and reduced secondary material losses during procedures, they generate mixed waste (i.e. Waste Electrical and Electronic Equipment, WEEE, potentially hazardous dust containing nanoparticles and volatile organic compounds, contaminated liquid waste). Although quantitative data for typical dental femtosecond laser protocols remain limited, this waste is not large compared to the total waste produced by a healthcare institution, but it is specific and requires proper management [41 - 43].

The use of femtosecond lasers therefore enables a significant reduction in the use of harmful chemicals in dentistry, which has a positive impact on patient health and reduces chemical pollution of the environment [44, 45].

## CONCLUSION

The use of lasers in dentistry represents a significant advance in the treatment of oral diseases and brings numerous benefits to patients, such as faster recovery, less pain and greater precision in treatment. The

environmental benefits of lasers in dentistry, such as reduced medical waste, lower energy consumption and reduced use of chemicals, make it not only a technically advanced but also an environmentally friendly solution. The development of laser technology in dentistry can play a key role in improving the sustainability of dentistry by helping to reduce the negative impact on the environment and improve patient health.

Femtosecond laser technology sets new standards in dentistry by combining exceptional precision, minimal invasiveness and great clinical versatility. Its unique operating mechanism, based on ultra-short pulse durations, enables highly controlled interaction with tissue, making it particularly valuable for procedures involving both hard and soft dental tissue. In addition to its clinical benefits, the femtosecond laser supports the shift towards environmentally friendly dentistry by reducing the need for disposable materials, minimising aerosol production and eliminating the need for chemical agents. The femtosecond laser is an innovative tool as dental practises increasingly prioritise patient comfort, efficiency and environmental sustainability. The integration of the femtosecond laser into modern dentistry not only improves treatment outcomes, but is also in line with a broader vision of holistic and sustainable healthcare. This paper provides a comprehensive overview of the current application of the femtosecond laser in dentistry and provides useful information for dentists, researchers and other professionals in the field of dentistry.

## REFERENCES

- [1] A. Sachdeva, A. Sharma, S. Bhateja, G. Arora, Green Dentistry: A Review, *Journal of Dentistry and Oral Biology* 3(2018) 6, Article 1144.
- [2] D.M. Hackley, J. Luca, Sustainability in Dentistry: An Overview for Oral Healthcare Team Members, *Journal of the California Dental Association* 52(2024) 1, Article 2422150.

- <https://doi.org/10.1080/19424396.2024.2422150>
- [3] G. Thomas, R. Isaacs, Basic principles of lasers, *Anaesthesia & Intensive Care Medicine* 12(2011) 12, 574-577. <https://doi.org/10.1016/j.mpaic.2011.09.013>
- [4] L. Sachelarie, R. Cristea, E. Burlui, L.L. Hurjui, Laser Technology in Dentistry: From Clinical Applications to Future Innovations, *Dentistry Journal* 12(2024) 12, Article 420. <https://doi.org/10.3390/dj12120420>
- [5] S.K. Verma, S. Maheshwari, R.K. Singh, P.K. Chaudhari, Laser in dentistry: An innovative tool in modern dental practice, *National Journal of Maxillofacial Surgery* 3(2012) 2, 124-132. <https://doi.org/10.4103/0975-5950.111342>
- [6] S.K. Vaddamanu, R. Vyas, K. Kavita, R. Sushma, A.S. Aboobacker, A. Dixit, A. Kumar, In vitro Evaluation of Laser vs. Handpiece for Tooth Preparation, *Journal of Pharmacy And Bioallied Sciences* 14(2022), Suppl 1, S526-S529. [https://doi.org/10.4103/jpbs.jpbs\\_95\\_22](https://doi.org/10.4103/jpbs.jpbs_95_22)
- [7] A. Al Shammari, J. Roffie, F.M. Suhaimi, N.R.N.A. Ghani, Lasers in dentistry: An overview, *Journal of International Dental and Medical Research* 17(2024) 4, 1754-1761.
- [8] M.A.M Alghamdi, M. Halawani, H.A. Alarawi, A.M. Alzaidi, L.H. Alhogail, S.W.O Alsobhi, A.H.M. Alamrai, J.A.M. Alrashedi, A.N.B. AlRashidi, T.A.A. Al-Ghamdi, The Use of Laser Technology in Dentistry: A Comprehensive Review, *Migration Letters* 19(2022) S5, 577-586.
- [9] T.P. Callou, R. Garcia, A. Mukai, N.T. Giacomini, R.G. de Souza, S.J. Bechara, Advances in femtosecond laser technology, *Clinical Ophthalmology* 10(2016), 697-703. <https://doi.org/10.2147/OPHTH.S99741>
- [10] R. Paschotta, Femtosecond Lasers, *RP Photonics Encyclopedia*, 2025. <https://doi.org/10.61835/6si>
- [11] K. Filipek, A. Pisklak, H. Behrendt, M. Głód, M. Węgrzynek, Ultrashort pulse lasers in medicine, current applications and prospects for future advances, *Medical Science* 28(2024) 152, Article e130ms3422. <https://doi.org/10.54905/disssi.v28i152.e130ms3422>
- [12] S.S. Harilal, J.R.F. Freeman, P.K. Diwakar, A. Hassanein, Femtosecond Laser Ablation: Fundamentals and Applications, in: *Laser-Induced Breakdown Spectroscopy*, eds.: S. Musazzi, U. Perini, Springer Berlin, Heidelberg, 2014, 143-166. [https://doi.org/10.1007/978-3-642-45085-3\\_6](https://doi.org/10.1007/978-3-642-45085-3_6)
- [13] M. Calvarese, T. Meyer-Zedler, M. Schmitt, O. Guntinas-Lichius, J. Popp, Recent developments and advances of femtosecond laser ablation: Towards image-guided microsurgery probes, *Trends in Analytical Chemistry* 167(2023), Article 117250. <https://doi.org/10.1016/j.trac.2023.117250>
- [14] V.L. Lagunov, M. Rybachuk, A. Itthagarun, L.J. Walsh, R. George, Modification of dental enamel, dentin by an ultra-fast femtosecond laser irradiation: A systematic review, *Optics & Laser Technology* 155(2022), Article 108439. <https://doi.org/10.1016/j.optlastec.2022.108439>
- [15] L. Rapp, S. Madden, J. Brand, K. Maximova, L.J. Walsh, H. Spallek, O. Zuaiteir, A. Habeb, T.R. Hirst, A.V. Rode, Investigation of laser wavelength effect on the ablation of enamel and dentin using femtosecond laser pulses, *Scientific Reports* 13(2023) 1, Article 20156. <https://doi.org/10.1038/s41598-023-47551-5>
- [16] E.-G.C. Tzanakakis, E. Skoulas, E. Pepelassi, P. Koidis, I.G. Tzoutzas, The use of lasers in dental materials: A review, *Materials* 14(2021) 12, Article 3370. <https://doi.org/10.3390/ma14123370>
- [17] M.H. Niemz, Cavity Preparation with the Nd:YLF Picosecond Laser, *Journal of Dental Research* 74(1995) 5, 1194-1199. <https://doi.org/10.1177/00220345950740050801>

- [18] P. Pike, C. Parigger, R. Splinter, P. Lockhart, Temperature distribution in dental tissue after interaction with femtosecond laser pulses, *Applied Optics* 46(2007) 34, 8374-8378. <https://doi.org/10.1364/ao.46.008374>
- [19] H. Chen, H. Li, Y.C. Sun, Y. Wang, P.J. Lü, Femtosecond laser for cavity preparation in enamel and dentin: Ablation efficiency related factors, *Science Reports* 6(2016), Article 20950. <https://doi.org/10.1038/srep20950>
- [20] F. Javed, R. Akhter, V. Miletic, Effects of femtosecond laser on hard dental tissues: A scoping review, *Lasers in Medical Science* 39(2024), Article 286. <https://doi.org/10.1007/s10103-024-04225-6>
- [21] L. Rapp, S. Madden, J. Brand, L.J. Walsh, H. Spallek, O. Zuaite, A. Habeb, T.R. Hirst, A.V. Rode, Femtosecond laser dentistry for precise and efficient cavity preparation in teeth, *Biomedical Optics Express* 13(2022) 9, 4559-4571. <https://doi.org/10.1364/boe.463756>
- [22] H.H. Casarin, V.S. Mattos, J.C. de Castro Neto, M.A. Chinelatti, Chemical and morphological changes of femtosecond laser-irradiated enamel using subablative parameters, *Microscopy Research & Technique* 84(2021) 10, 2399-2408. <https://doi.org/10.1002/jemt.23795>
- [23] T. Petrov, E. Pecheva, A.D. Walmsley, S. Dimov, Femtosecond laser ablation of dentin and enamel for fast and more precise dental cavity preparation, *Materials Science and Engineering: C* 90(2018), 433-438. <https://doi.org/10.1016/j.msec.2018.04.070>
- [24] H. Kandil, E. Ahmed, N. Fouad, O. Ali Dabbous, M. Niazy, T. Mohamed, Using Femtosecond Laser Light-Activated Materials: The Biomimetic Dentin Remineralization Was Monitored by Laser-Induced Breakdown Spectroscopy, *Medicina* 59(2023) 3, Article 591. <https://doi.org/10.3390/medicina59030591>
- [25] L. Niu, W. Zhang, D.H. Pashley, L. Breschi, J. Mao, J. Chen, F.R. Tay, Biomimetic remineralization of dentin, *Dental Materials* 30(2014) 1, 77-96. <https://doi.org/10.1016/j.dental.2013.07.013>
- [26] P.G. Spizzirri, N.J. Cochrane, S. Praver, E.C. Reynolds, A comparative study of carbonate determination in human teeth using Raman spectroscopy, *Caries Research* 46(2012) 4, 353-360. <https://doi.org/10.1159/000337398>
- [27] Y. Sun, J. Sun, X. Wu, Y. Li, X. Li, R. Li, T. Wang, W. Bi, W. Cui, Y. Yu, Mechanism of zirconia microgroove surface structure for osseointegration, *Materials Today Advances* 12(2021), Article 100159. <https://doi.org/10.1016/j.mtadv.2021.100159>
- [28] N. Sahoo, O. Carvalho, M. Özcan, F. Silva, J.C.M. Souza, A.-F. Lasagni, B. Henriques, Ultrashort pulse laser patterning of zirconia (3Y-TZP) for enhanced adhesion to resin-matrix cements used in dentistry: An integrative review, *Journal of the Mechanical Behavior of Biomedical Materials* 143(2023), Article 105943. <https://doi.org/10.1016/j.jmbbm.2023.105943>
- [29] W.A. Lackington, B. Bellon, S. Guimond, P. Schweizer, C. Cancellieri, A. Ambeza, A.-L. Chopard-Lallier, B. Pippenger, A. Armutlulu, X. Maeder, P. Schmutz, M. Rottmar, Bio-Inspired Micro- and Nano-Scale Surface Features Produced by Femtosecond Laser-Texturing Enhance TiZr-Implant Osseointegration, *Advanced Healthcare Materials* 13(2024) 23, Article 2400810. <https://doi.org/10.1002/adhm.202400810>
- [30] S.-M. Eun, K. Son, S.-M. Hwang, Y.-T. Son, Y.-G. Kim, J.-Y. Suh, J.H. Hwang, S.-M. Kwon, J.H. Lee, H.D. Kim, K.-B. Lee, J.-M. Lee, The Impact of Mechanical Debridement Techniques on Titanium Implant Surfaces: A Comparison of Sandblasted, Acid-Etched, and Femtosecond Laser-Treated Surfaces, *Journal of Functional Biomaterials* 14(2023) 10, Article 502. <https://doi.org/10.3390/jfb14100502>
- [31] V. García-Sanz, V. Paredes-Gallardo, C.

- Bellot-Arcís, L. Martínez-León, R. Torres-Mendieta, J. Montero, A. Albaladejo, Femtosecond laser settings for optimal bracket bonding to zirconia, *Lasers in Medical Science* 34(2019), 297-304. <https://doi.org/10.1007/s10103-018-2589-3>
- [32] M.M. Alsarani, O. Alsadon, O. Alageel, N. Alfrisany, Z. Almutairi, M.A. Al-Gawati, M. Almozainy, The Effect of Femtosecond Laser Surface Patterns on the Effectiveness of Resin Composite to Zirconia Bonding, *Journal of Functional Biomaterials* 14(2023) 10, Article 508. <https://doi.org/10.3390/jfb14100508>
- [33] W. Chen, F. Yuan, S. Liang, C. Qu, S. Lin, X. Li, L. Yan, X. Shi, W. Yi, Parameter optimization of femtosecond laser pulses for implant cavity preparation, *Biomedical Optics Express* 16(2025) 2, 460-472. <https://doi.org/10.1364/BOE.546367>
- [34] S. Liang, J. Zheng, F. Yuan, Preliminary study on the osseointegration effects of contactless automated implant cavity preparation via femtosecond laser ablation, *Biomedical Optics Express* 13(2022) 1, 89-92. <https://doi.org/10.1364/BOE.446602>
- [35] J. Zheng, X. Zhang, Y. Zhang, F. Yuan, Osteoblast differentiation of bone marrow stromal cells by femtosecond laser bone ablation, *Biomedical Optics Express* 11(2020) 2, 885-894. <https://doi.org/10.1364/BOE.383721>
- [36] N. Touya, S. Al-Bourgol, T. Désigaux, O. Kérourédan, L. Gemini, R. Kling. R. Devillard, Bone Laser Patterning to Decipher Cell Organization, *Bioengineering* 10(2023) 2, Article 155. <https://doi.org/10.3390/bioengineering10020155>
- [37] J. Lietz, A. Kozak, A. Nienhaus, Prevalence and occupational risk factors of musculoskeletal diseases and pain among dental professionals in Western countries: A systematic literature review and meta-analysis, *PLoS One* 13(2018) 12, Article e0208628. <https://doi.org/10.1371/journal.pone.0208628>
- [38] S.V. Patel, L.J. Maguire, J.W. McLaren, D.O. Hodge, W.M. Bourne, Femtosecond Laser versus Mechanical Microkeratome for LASIK. A Randomized Controlled Study, *Ophthalmology* 114(2007) 8, 1482-1490. <https://doi.org/10.1016/j.ophtha.2006.10.057>
- [39] A.M. Roszkowska, M. Urso, A. Signorino, P. Aragona, Use of the Femtosecond Lasers in Ophthalmology, *EPJ Web of Conferences* 167(2018), Article 05004. <https://doi.org/10.1051/epjconf/201816705004>
- [40] J.-H. Park, K.-B.-D. Son, Y.-T. Son, Y.-G. Kim, S.-M. Hwang, J.-H. Hwang, J.-H. Lee, H.-D. Kim, K.-B. Lee, J.-M. Lee, Comparative Evaluation of Laser System to Conventional Surgical Approaches in Periodontal Healing Using Optical Coherence Tomography, *Applied Sciences* 14(2024) 19, Article 8854. <https://doi.org/10.3390/app14198854>
- [41] K.W. Kolasinski, M.C. Gupta, L.V. Zhigilei, Plume and nanoparticle formation during laser ablation, in: *Encyclopedia of Interfacial Chemistry: Surface Science and Electrochemistry*, Vol. 2, ed.: K. Wandelt, Elsevier, Oxford, 2018, 594-603. <http://dx.doi.org/10.1016/B978-0-12-409547-2.14045-4>
- [42] F. Van der Weijden, Aerosol in the oral health-care setting: a misty topic, *Clinical Oral Investigations* 27(2023), 23-32. <https://doi.org/10.1007/s00784-023-05034-x>
- [43] N. Joy, A.-M. Kietzig, In situ collection of nanoparticles during femtosecond laser machining in air, *Nanomaterials* 11(2021) 9, Article 2264. <https://doi.org/10.3390/nano11092264>
- [44] R.J.G. De Moor, J. Verheyen, A. Diachuk, P. Verheyen, M.A. Meire, P.J. De Coster, F. Keulemans, M. De Bruyne, L.J. Walsh, Insight in the chemistry of laser-activated dental bleaching, *The Scientific World Journal*, Volume 2015, Article 650492. <https://doi.org/10.1155/2015/650492>
- [45] V.C. Pereira da Fonseca, L.G. Abreu,

E.J. Andrade, N. Asquino, R.P. Esteves Lima, Effectiveness of antimicrobial photodynamic therapy in the treatment of peri-implantitis: systematic review and meta-analysis, *Lasers in Medical Science* 39(2024), Article 186. <https://doi.org/10.1007/s10103-024-04135-7>

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