APPLICATION OF LASERS AND LASER PROCESSING TECHNOLOGIES IN MODERN DENTISTRY: A REVIEW

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ABSTRACT

The purpose of this overview is to analyze the application of different types of lasers and laser processing technologies in modern dentistry. The analysis is based on the classifications of lasers according to several main characteristics, including active medium and spectral range, mode of operation and power, energy efficiency and accuracy. Two main groups of applications are considered: 1) for processing materials and manufacturing dental constructions and 2) for diagnostics and treatment in dentistry.

It has been established that lasers of almost all types and powers are used in dentistry. Lasers with high power, collimation and high energy density are used for surface heat treatment and texturing of metal surfaces, as well as for the fabrication of dental constructions from metals and alloys by laser cutting, welding and selective laser melting. The types of lasers used for clinical applications are determined by the wavelength, the interaction with the tissues, the laser's radiation mode and its power. In dentistry, a variety of lasers are used in the treatment of caries and root canals, surgical cutting and coagulation of soft tissues, accelerated wound healing, reduction of inflammation and swelling. The great variety of lasers and their advantages enable them to enter dentistry more widely in recent years, not only for the production of dental constructions, but also in clinical practice.

Keywords: lasers, laser-processing technologies, materials processing, clinical applications, dentistry.

INTRODUCTION

The laser is an optical quantum generator (LASER - Light Amplification by Stimulated Emission of Radiation) of monochromatic, coherent and directional electromagnetic radiation with high energy density. It emits light based on the processes of stimulated emission of photons and inverse population of energy levels. With each act of stimulated emission, the number of photons increases by one, and the generated photons have the same phase, frequency, direction of propagation, and polarization as the ones that stimulated them. The presence of a constant phase in the induced and stimulating light for the laser radiation enables it to be used to transmit information by modulation, and the high collimation of the beam allows the transmission of energy and information over long distances. The combination of propagation with the possibility of creating short-term laser pulses is a prerequisite for generating pulses with enormous power of the order of giga- and terawatts, which are widely used in laser technologies. In the last two decades, lasers have been widely used in dental practice, not only in caries detection diagnostics [1], but also in tartar removal therapy, root canal disinfection [2] and as a cutting tool for hard dental tissues [3]. Due to the reduced sensitivity when working with a laser, the number of applications for processing hard and soft tissues in dentistry is increasing [4 - 6].

In addition to the clinic, lasers are now also used in dental laboratories for the production of prosthetic constructions from various materials - polymers, composites, ceramics, metals and alloys [7]. When working with metals, the processes of laser welding, laser texturing of metal surfaces, 3D printing, better known as selective laser melting (SLM), and laser surface heat treatment are mostly applied. The first process is used to connect the individual elements in the production of the metal skeletons of multi-unit metal-ceramic dental bridges and prosthetic constructions. In the second process, the roughness of the metal surface is increased by impact with a laser, which leads to an increase in the adhesion between the ceramic and the alloy in metal-ceramic prostheses or to an increase in the biocompatibility of titanium implants [8, 9]. And, with the help of the SLM process, complex details can be produced not only for metal-ceramic dental prostheses, but also for personal implants in maxillofacial surgery from Ni-Cr, Co-Cr and Ti alloys [10 - 13]. In laser heat treatment, only individual areas of the detail are affected, which changes the structure of the surface layer. This leads to an increase in hardness and corrosion resistance, and hence tower resistance [14 - 19].

The purpose of this overview is to analyze the application of different types of lasers and laser processing technologies in modern dentistry. The analysis is based on classifications of lasers according to several main characteristics, including active medium and spectral range, mode of operation and power, energy efficiency and accuracy. Two main groups of applications are considered: 1) for processing materials and making dental constructions and 2) for diagnostics and treatment in dentistry.

CLASSIFICATION OF LASERS

Lasers in medicine can be classified according to different factors. Fig. 1 presents some of the main classifications.

According to the type of active medium, lasers can be liquid and gas active medium, solid-state, semiconductor and fibre-optic (Fig. 1). The liquid active medium can be a solution of organic dyes such as rhodamine, pyromine, trypaflavin or of rare earth elements. In them, the wavelength of the laser radiation can be changed. Gas lasers can be based on active medium of gas molecules (CO_2 laser), of neutral atoms (helium-neon laser), of ionized atoms (argon and krypton laser) or of metal vapours (copper vapour laser). For the active medium in solid-state lasers, solid crystals such as ruby and alexandrite or neodymium-enriched glasses are used. Typical examples are Nd:YAG (neodymium-yttrium aluminium garnet) and Er:YAG (erbium-yttrium aluminium garnet) lasers. Semiconductor lasers have

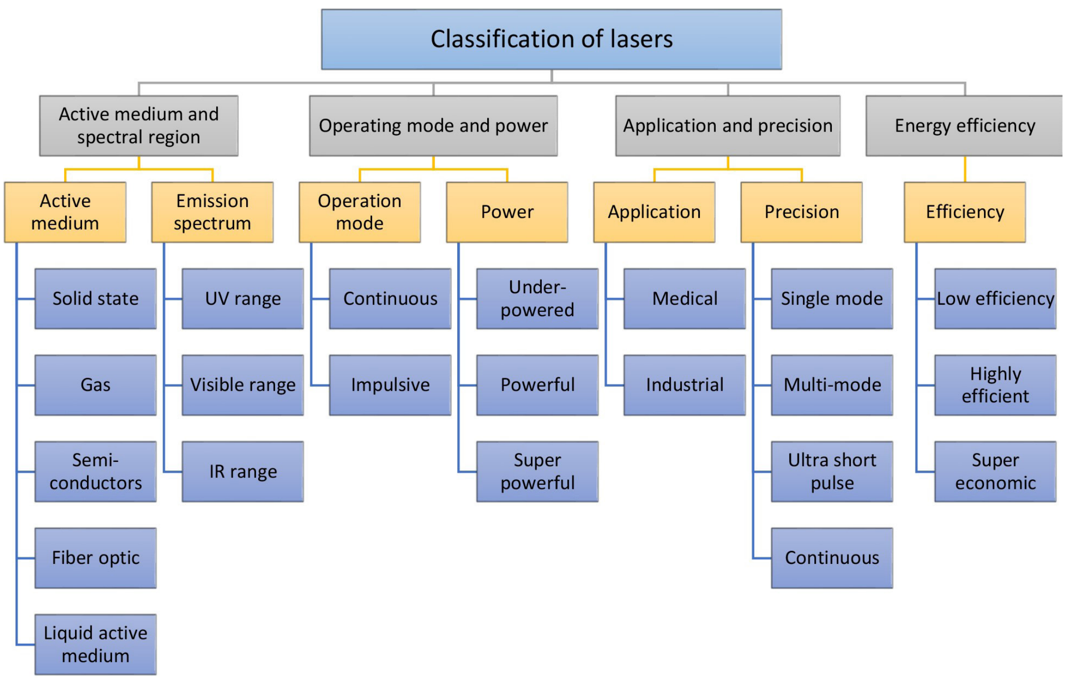

Fig. 1. General classification of lasers.

an active medium of a semiconductor, most commonly gallium arsenide. Typical example of this type of laser are diode lasers.

According to the spectral range of light emission, lasers are divided into those operating in the ultraviolet, visible and infrared regions (Fig. 1). And according to the working mode, there are two types - continuous and pulsed. In continuous lasers, emission and absorption are continuous processes, while in pulsed lasers, periods of excitation and emission with varying repetition rates are observed.

Depending on the power, lasers are of low, high and ultra-high power (Fig. 1). Low-power lasers are used for medical and cosmetic applications, while high-power and ultra-power lasers are used for cutting and welding metals for industrial applications.

According to the laser beam targeting precision, lasers are divided into: 1) single-mode, generating radiation with high precision in a narrow spectral range; 2) multimode lasers generating a beam in a wide spectral range with greater dispersion, used more often in industry, and 3) pulsed lasers with a pulse length from a few pico- to a few femtoseconds, finding application in multiphoton microscopy, in laser surgery and microprocessing of materials. Fig. 2 presents a wavelength classification of the most commonly used lasers in dentistry [20, 21]. The Er:YAG laser radiation (2940 nm), whose wavelength coincides with the absorption peak of water in the IR range, is more strongly absorbed by hydroxylapatite compared to that of CO_2 and Nd:YAG lasers [22]. It has been used in root canal treatment and pulpotomy [23, 24]. The Er,Cr:YSGG laser (2780 nm) has similar applications and limitations in its use in dental practice as the Er:YAG laser, as they belong to the same group. It has one advantage - when irradiating the dental tissues, a water spray is used, which is not related to the generation of heat, due to the lack of friction [25]. The Nd:YAG laser is a pulsed laser with a wavelength of about 1064 nm with low absorption by the water, with the possibility of dissipating its energy and penetrating into adjacent tissues [26].

The CO_2 gas laser (10 600 nm) is widely used in medicine and dentistry because it can control blood loss in various invasive interventions or in direct pulp closure in dentistry [27]. The easy absorption of its radiation by the tooth enamel and dentin can be considered negative because it can cause cracks on the tooth enamel surface, which leads to the growth of microorganisms, which in turn leads to the occurrence of caries [28].

Diode lasers with wavelengths of 810 nm/980 nm are of low power. Due to high water absorption in that region and their large optical divergence, they are mainly used in the treatment of root canals in order to eliminate microorganisms in them [29, 30].

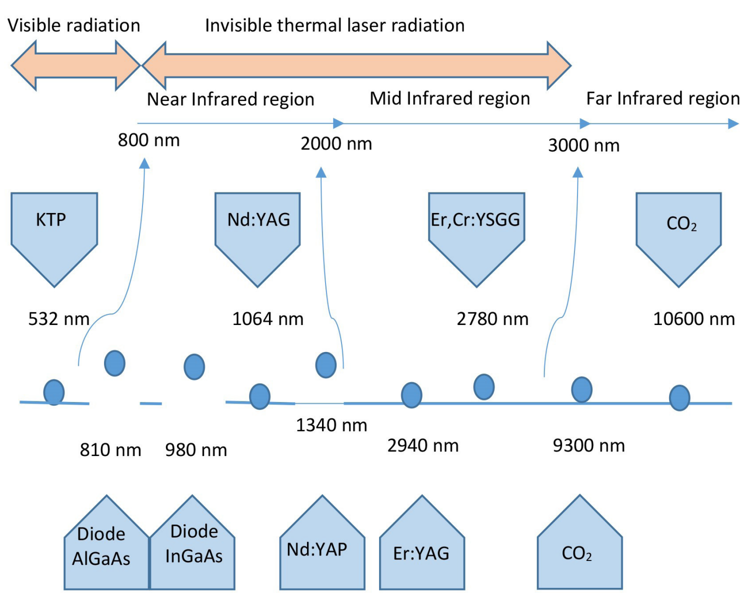

Fig. 2. Classification of the most commonly used lasers in dentistry according to the radiation wavelength.

MECHANISM OF INTERACTION OF LASER RADIATION WITH MATERIALS AND LIVING TISSUES

The impact of laser radiation on surfaces of dental materials or on living tissues of the oral cavity is accompanied by energy absorption. The amount of absorbed energy depends on the type of material and the parameters of laser radiation - pulseduration, wavelength, repetition rate, power [31].

The optical properties of bones as classical composite tissues, built of hydroxylapatite, collagen and proteins determine the interaction of laser radiation with the substance. This interaction depends on the water and mineral content, the density of the tissues, and the tooth enamel pigmentation. There are data on different effects of lasers on tissues in the oral cavity. Nd:YAG (1064 nm) and diode (800 nm to 950 nm) lasers have lower absorption coefficients in water, but are highly adsorbed by pigmented tissues. Er,Cr:YSGG and Er:YAG (2780 nm and 2940 nm) radiation is strongly absorbed by hydroxylapatite in teeth [32]. To achieve good results, the dentist must assess for each patient the prescribed therapy or performance of the relevant procedure.

The interaction of laser radiation with materials used to make dental prostheses is different: one of the ways of interaction is direct removal of material by laser ablation [33 - 35], and the second is performing controlled surface modification of solid materials [36, 37], which leads to an increase in roughness and obtaining a certain surface texture. In ceramic and polymer samples, multiphoton absorption and nonlinear optical processes are observed when high-intensity laser radiation falls on them [38, 39].

APPLICATION OF LASERS AND LASER TECHNOLOGIES IN DENTISTRY

The broad possibilities of laser radiation action allow it to be used in two main directions of dental medicine. The first is the application of laser technologies for the materials surface modification in order to increase their properties and make customized constructions with a complex shape in implantology and dental prosthetics [7]. In the second direction, technologies are being developed for more effective and painless diagnosis and treatment of oral diseases of the soft and hard tissues [40, 41].

Application of laser technologies for materials processing

Fig. 3 presents the main materials used in dentistry and their possibilities for laser processing [42]. On the other hand, Fig. 4 shows a classification of the types of lasers for processing different materials in dental practice [43].

Laser cutting

When making bridge constructions, errors occur as a result of metal alloys shrinkage in the casting process. To correct them, laser cutting is applied at certain places

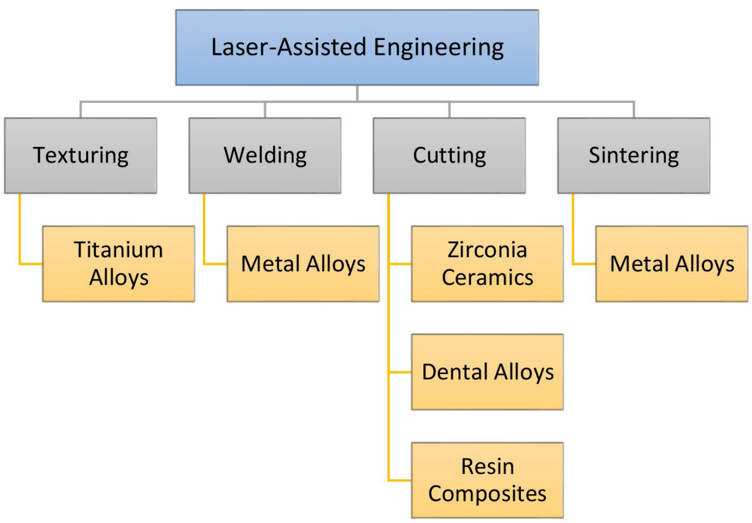

Fig. 3. Basic applications of lasers in materials processing in dentistry.

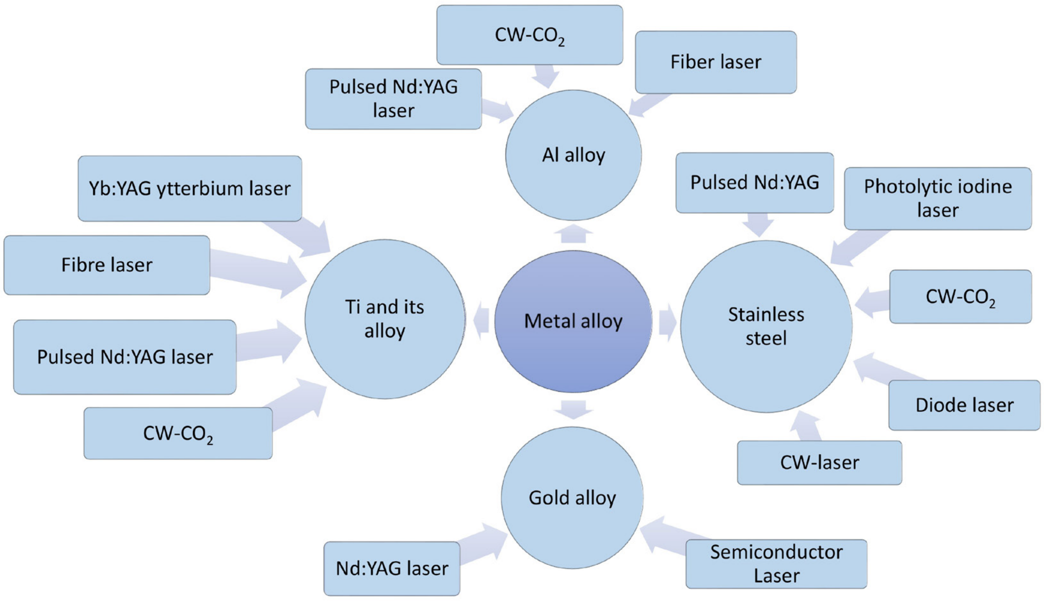

Fig. 4. Types of materials and types of lasers used to process them.

in the construction and subsequent welding. This is done with the help of powerful lasers, most often carbon ones. The techniques commonly used are laser cutting based on the melting principle accompanied by internal gas production, or based on vaporization and chemical degradation [44]. The advantages of laser cutting include high speed and accuracy as well as free of contamination process [45]. Special powerful femtosecond lasers have been developed for processing zirconium ceramics, increasing the quality and productivity of zirconium constructions [46]. Most often, erbium (Er:YAG) and erbium-chromium (Er,Cr:YSGG) lasers are used for this purpose [47].

Laser welding

Due to its high power, collimation and high energy density, laser radiation is used for fine welding. Weldments obtained by this method have a smooth surface, homogeneous microstructure and small deformation [41]. In dental practice, the specified technology is used to process metals such as stainless steel, titanium, noble and base alloys, ceramic and polymer materials. To obtain quality weldments, the use of longer laser pulses is more suitable, as it is possible to heat the material to the melting point without vaporizing it. Low-power laser pulses are used for surface welding [48]. The lasers used for this purpose are high-energy ones of the Nd:YAG, diode and femtosecond type.

Laser welding in manufacturing dental constructions has several advantages: precision, minimal losses of the processed material and a lower risk of defects due to minimal heat impact. The application of laser welding in dentistry is the most diverse - from the repair of dental crowns and bridges to the restoration of dental implants, repair of prostheses and fixation of orthodontic elements.

Many studies have been made on the effect of laser welding for various dental alloys. The influence of the weld spot diameter and the penetration depth on the mechanical properties and corrosion resistance of the welded materials have been analysed [41]. Treatment of gold alloys with the Nd:YAG laser results in poor thermal absorption. In order to reduce the reflectivity of this type of material before welding, it is proposed to use a black marker, increased current magnitude and reduced spot diameter [49].

An increase in weld strength was found in the aging process. Double-welded gold alloys demonstrate increased strength compared to single-welded ones. A study was done by Goldman et al. [50] on the possibility of replacing soldering of a fixed partial denture with laser welding with the potential use of CO_2 and Nd:YAG lasers. Bertrand et al. [51] studied the laser welding (Nd:YAG laser) of Ni-Cr-Mo and Cr-Co-Mo alloys and proved that the Co-Cr alloy showed excellent weldability and Ni-Cr - poor, probably caused by the high amount of boron and carbon. Iwasaki et al. [52] studied the weldments of Ag-Pd-Au, Au-Pt-Ag and Ti dental alloys made by Nd:YAG pulsed laser and found increased hardness in the weld zone and lower strength. Santos et al. [53] studied dental implants made of laser-welded Ag-Pd-Au-Cu alloys and as a result demonstrated exceptional resistance to corrosion in the weld zone region compared to base metals in a simulated oral cavity environment.

Additive technologies

The production of details through additive technologies, or better known as 3D printing, is carried out by CAD/CAM systems based on a pre-designed 3D virtual model. The virtual model is generated by the CAD module, and the construction is manufactured by the CAM module, which actually represents the production machine. In additive technologies, the details production itself is carried out by adding material [10, 12]. In practice, the entire range of known materials can be used - polymers, ceramics, metals and alloys. In additive technologies, the material is in the form of a layer of powder or liquid, which is connected to the previous layer by means of polymerization, melting or bonding through various processes. The main additive technologies currently include: stereolithography (SLA), selective laser sintering (SLS), selective laser melting (SLM), fused deposition modelling (FDM) and ink-jet printing (IJP) [7, 54 - 58]. Lasers are used in three of the processes listed: laser stereolithography and selective laser sintering/melting. The application of the above methods allows to obtain constructions applicable in various fields of dentistry such as metal frameworks for dental prostheses, customized implants in maxillofacial surgery, implant guides, plastic models for casting metal frameworks, etc. [59 - 70]. The resulting complex objects can be of the same or different material, and their production is quick and easily controllable.

Laser stereolithography

In stereolithography process, photopolymerizing monomers, oligomers, and composites based on polymethyl methacrylate (PMMA) are used. In most 3D printers, a laser beam is used as a light source, working by scanning the area (Fig. 5). Based on the type of materials, in dentistry this technology is used for the production of: models to replace plaster casts in prosthetic dentistry and orthodontics; individual impression trays and denture bases; surgical guides for implants; temporary crowns and bridges, as well as models for casting dental constructions from metals and alloys [10, 56 - 58].

Selective laser melting

Selective laser melting technology uses the high concentration of energy from a laser beam to melt and fuse metal powders into three-dimensional objects. During scanning, the metal powder (Fig. 6) absorbs a large amount of energy from the laser radiation and this

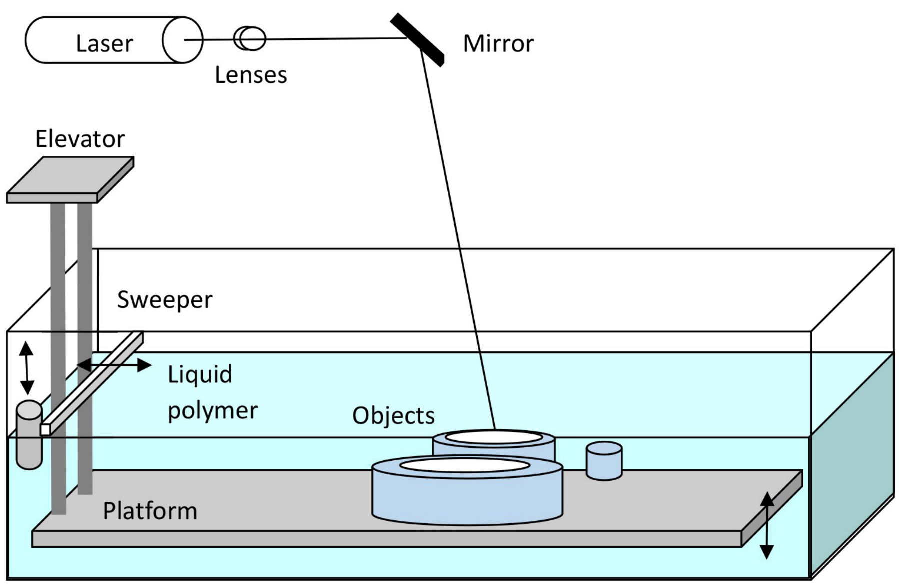

Fig. 5. Scheme of laserstereolithography [7].

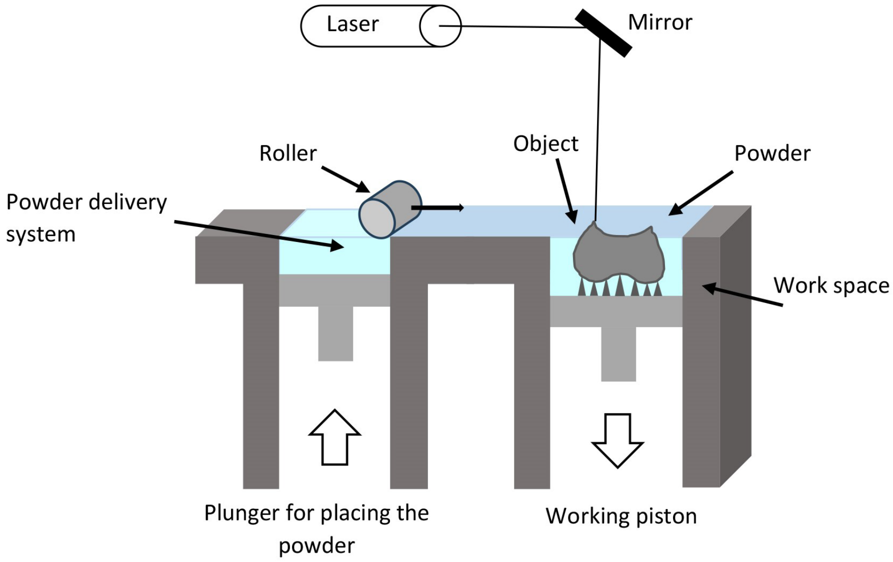

Fig. 6. Scheme of selective laser melting process.

causes the temperature to rise above the metal's melting point. During the laser beam movement on the surface, the temperature quickly decreases and this leads to the formation of a good solder between the different layers. SLM is used to produce dental implants, crowns, bridges and other metal constructions, as the manufactured complex details have high mechanical strength [10 - 12].

The high-quality dental details obtained by this process have properties that are determined by the power of the laser beam, the scanning speed, the energy density of the radiation, the difference in the cooling rates near and far from the melting zone caused by the laser radiation [71].

Application of lasers for diagnosis and treatment

Diagnostic applications

Argon and diode lasers are applied in the diagnosis of dental caries. Diode lasers are used for calculus detection and for Doppler fluorimetry of pulp blood flow [72]. Diode lasers are also used in gum correction surgery, providing painless and bloodless procedures, as well as quick recovery and faster wound healing. Those lasers are effective in the treatment of oral aphthous stomatitis [73]. With their application, both pain decrease and oral cavity wounds size decrease were observed. The recommended parameters of the laser radiation are a wavelength of 810 nm and a power of up to 1MW [74].

Clinical applications

Erbium laser demonstrate good efficiency in removing caries without damaging the pulp tissue as in rubies [75]. They are used for ablation and removal of hard tissues in root canal treatment [24]. Erbium lasers are highly efficient, using a large part of the radiation energy for the treatment procedure, and a very small part is transformed into heat losses. The use of highly efficient lasers reduces the risk of thermal damage to the surrounding dental and tissue material, improves precision and safety when performing invasive medical procedures, reduces pain and discomfort for the patient, and helps to quickly recover after the procedure. However, control of the laser pulse energy and the repetition rate of the procedures is necessary to avoid cracks in the tooth enamel [76].

Both types - CO_2 and Nd:YAG lasers are powerful, often used in dental practice. The first one is used for rapid removal of soft tissues located at a shallow depth, as it is known to be able to control haemorrhages and to close the pulp [27]. However, because its radiation is strongly absorbed by water, it should be used with care due to the possibility of cracks in the tooth enamel [77]. The Nd:YAG laser is effective in surgical cutting and coagulation of soft tissues [75].

The Nd:YAP laser is used in pulse mode in order to avoid the thermal effect on surrounding tissues. It is effective in stain removal [78, 79] as well as energy transfer in curved dental canals [80].

Diode lasers are used for aesthetic reconstruction of the gums, to remove inflammation and lengthen the tooth crown. Lasers are also used in low-level applications laser therapy. Here, laser radiation is used to therapeutically accelerate wound healing, reduce inflammation and oedema [81, 82].

The laser can help shape the root canal, reducing the risk of infection during treatment. For this purpose, it is used to evaporate the water from the hard tooth tissue and ablate the surface tissue in the canal. The use of the Er:YAG laser has been proven to reduce the risk of root fractures [23], as well as providing better efficiency in cleaning the canal walls [83].

Er:Cr:YSGG and Er:YAG lasers are increasingly being used for efficient, safe and controllable removal of dental facets [84, 85]. Debonding the facet without damaging the tooth structure at a distance between the laser tip and the tooth structure of 2 mm takes up to 10 seconds [86, 87].

Another type of lasers commonly used in dentistry are the short-pulse ones, generating pulses in the picosecond and femtosecond range. Due to their high precision and ability to control the laser radiation, they are suitable for micromachining of materials as well as for laser surgery. Nanosecond pulsed lasers are capable of storing and releasing energy very quickly on the order of nanoseconds. Their power can reach tens of kilowatts, which allows their use in the ablation of various materials [88]. Another type of pulsed lasers are femtosecond lasers, operating in a wide spectral range, generating pulses of high intensity and a range of frequencies. These ultrafast pulses are useful due to their high peak power for the development of multiphoton excitation techniques convenient for obtaining three-dimensional imaging of living tissue [89]. They are also used for precise micromachining of materials - cutting, joining and processing of fine details.

CONCLUSIONS

In this paper, an analysis of the application of different types of lasers and laser processing technologies in modern dentistry has been made based on a comprehensive review of the literature. Several classifications of lasers are presented depending on their production parameters, the interaction of radiation with materials and living tissues and the type and processing technology of a given material.

It has been established that lasers of almost all types and powers are used in dentistry. They are mainly used in two directions: 1) for processing materials and manufacturing dental constructions and 2) for diagnosis and treatment.

Lasers with high power, collimation and high energy density are used for surface heat treatment and texturing of metal surfaces, as well as for the fabrication of dental constructions from metals and alloys by laser cutting, welding and selective laser melting.

The types of lasers that are used for clinical applications are determined by the wavelength, the interaction with the tissues, the laser's radiation mode and its power. In dentistry, a variety of lasers are used in the treatment of caries and root canals, surgical cutting and coagulation of soft tissues, accelerated wound healing, reduction of inflammation and swelling.

The great variety of lasers and their advantages enable them to enter dentistry more widely in recent years, not only for the production of dental constructions, but also in clinical practice.

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