Use of carbon dioxide lasers in dentistry

Abstract

Carbon dioxide (CO_2*) lasers have been used clinically in medicine and dentistry for over two decades. The optical property of* CO_2 *lasers in water makes them a fitting wavelength for soft tissue surgery. The 10,600-nm* CO_2 *laser is a readily available dental laser on the market. It enables performance of a bloodless surgical procedure and reduces post-operative discomfort in soft tissue dental surgery. Due to the advancement of technology,* CO_2 *lasers with short pulse duration and high peak power are available. This new-parameter* CO_2 *laser causes less collateral thermal damage to soft tissue than conventional lasers with continuous wave mode. Recent advancements allow transversely excited atmospheric pressure (TEA)* CO_2 *lasers to be delivered in a few microsecond pulses, at a high frequency, and with low fluence and enable them to vaporise hard dental tissue without carbonisation and pulpal damage. Recently, a 9,300-nm wavelength* CO_2 *laser has been introduced for clinical use in hard dental tissue removal. These developments make* CO_2 *lasers fitting for hard dental tissue preparation. In this paper, the production of* CO_2 *lasers and their technological advancements, optical properties, and parameters in relation to clinical applications in dentistry will be discussed.*

Introduction

Laser is an acronym that stands for light amplification by stimulated emission of radiation [1]. The photons that make up a laser beam are coherent, amplified in phase (standing wave) of a specific wavelength (monochromatic). Laser has been used in dentistry for over two decades [2]. Dental lasers are categorised according to their active medium and wavelengths. The currently available dental lasers are diode lasers (445 nm, 635 nm, and 810-980 nm), potassium titanyl phosphate (KTP) lasers (532 nm, Green), neodymium-doped yttrium aluminium garnet (Nd:YAG) lasers (1,064 nm), erbium lasers (2,780 nm and 2,940 nm), and carbon dioxide (CO_2) lasers (9,300 nm and 10,600 nm). Each wavelength of the lasers has a specific thermal output and a particular tissue interaction.

Dental lasers of different wavelengths are used to perform different procedures. Blue lasers, diode lasers, Nd:YAG lasers, and CO_2 lasers are primarily used in soft tissue surgery to provide good coagulation [3-6]. Because CO_2 lasers are well absorbed by water, they are absorbed on the surface of the soft tissue. The visible lasers (445 nm-660 nm) are absorbed within the first centimetre of the soft tissue because they are best absorbed by pigmented chromophores such as melanin and haemoglobin. Lasers with 810 nm to 1,064 nm wavelengths in the near infrared spectrum can penetrate into the soft tissue by a few centimetres because they are comparatively less well absorbed by melanin and haemoglobin. Erbium lasers, operating in free running pulse mode, are highest in water absorption, enabling their use for soft tissue ablation as well as for hard dental tissue and osseous preparation. The two erbium wavelengths commonly used in dentistry are erbium, chromium-doped yttrium, scandium, gallium, and garnet (Er,Cr:YSGG) lasers (2,780 nm) and erbium-doped yttrium aluminium garnet (Er:YAG) (2,940 nm) lasers. Although erbium lasers can also be used for soft-tissue procedures, bleeding control is less effective than with diode and CO_2 lasers, which offer better visualisation of the surgical site [6].

A CO_2 laser is a useful and efficient gas laser to be used in clinical dentistry. It is available at 10,600 nm on the market (Table 1). CO_2 lasers are often used in soft tissue surgery because they are well absorbed by water, which makes up 70% of biological tissues. They penetrate less than a millimetre [7, 8] and can produce excellent coagulation, along with a very precise cut. The optical property of the wavelength in tissue is important to determine the use of lasers to perform dental hard tissue preparation. Enamel and dentine are mainly composed of hydroxyapatite, which has a high absorption coefficient to the wavelengths of CO_2 lasers. Nevertheless, it takes time for a CO_2 laser to ablate dental hard tissues, which contain mainly hydroxyapatite, with a melting point over 1,600 ºC. The time required results in carbonisation, melting, and cracking of enamel [9-11].

The transversely excited atmospheric pressure (TEA) CO_2 laser [12] was developed by energizing a gas laser with a high voltage electrical discharge in a gas mixture, generally above atmospheric pressure. A pulsed low-energy CO_2 laser is available with very short pulse durations of a few microseconds with a high repetition rate (frequency) over 1000 Hz per second. These developments make CO_2 lasers fitting for dental hard tissue preparation [13]. In this paper, the production of CO_2 lasers and their technological advancement, optical properties, and parameters in relation to clinical applications in dentistry will be discussed.

Model	Company	Country
Miran	Mediclase Ltd	Cyprus, Israel
CYMA	Bison	Seoul, Korea
Surgical CO_2 laser	DOCTOR MED Co., Ltd.	Seoul, Korea
2015 Korea fractional CO2 laser	Daeshin Enterprise DSE	Seoul, Korea
Denta 2	GPT Inc	Nebraska, USA
Light scalpel	LightScalpel	Bothell, WA, USA
Opelaser Pro	Yoshida	Tokyo, Japan
SMART US20D	Deka	Calenzano, Italy

Table 1 Some 10,600 nm CO_2 lasers on the market

Production of CO_2 lasers

The CO_2 laser was one of the earliest gas lasers to be developed in 1964 [14]. It is one of the most useful and continuous wave lasers currently available. The lasing medium is a gas discharge, and the three main filling gases within the discharge tube are CO_2, nitrogen (N_2), and helium (He). With electrical discharge, microwave, or radiofrequency, electron impact excites the vibrational motion of N_2 molecules. This marks the beginning of the population inversion, where molecules in the system are in their excited states. N_2 cannot lose this energy by photon emission because it is a homonuclear diatomic molecule.

Excited vibrational levels are relatively long-lived and in a metastable state. The energy transfer that occurs due to the collision between N_2 molecules and CO_2 molecules causes vibrational (resonant) excitation of CO_2 molecules, with sufficient efficiency to lead to the required population inversion of CO_2 for laser operation (collision of the second kind). The N_2 molecules are then returned to ground state. The CO_2 molecules are still at a higher energy level after emission of photons. They return to ground state by colliding with cold He atoms. The resulting hot He atoms can be cooled by striking the bore (wall of the tube). The pressure in the tube must be low for adequate flow of photons. This limits the amount of CO_2 molecules in the tube, producing a low power laser. The photons emitted due to transition between energy levels have low energy and a longer wavelength than visible and near-infrared light because the energy levels of molecular vibration and rotation are similar.

Technological advancements of CO_2 lasers

More than one laser wavelength can be produced by a CO_2 gas laser. The wavelength depends on the isotope and resonator amplifying the wavelength desired. In dentistry, the 10,600-nm ($^{12}C^{16}O_2$ molecule) wavelength is the earliest and most commonly produced wavelength. A CO_2 laser is more efficient than other lasers because of its comparatively higher ratio of output power to pump power. Higher peak powers of CO_2 lasers can be achieved by slow flowing of the gas instead of using a sealed tube. Another method to achieve higher peak power is to increase the density of excited CO_2 molecules (i.e. the gas pressure). However, the voltage needed to achieve gas breakdown and couple energy into the upper laser levels also increases. The method to prevent producing a high voltage is to pulse the voltage transversely to the laser axis. Because electrical discharge can move transversely perpendicular to the laser axis, the electrons can travel at a substantially shorter distance and collide with more molecules [12]. Such a design is called the TEA CO_2 laser. The TEA CO_2 laser can achieve high peak power in short pulses (~2 μs) and at a high repetition rate.

The 9,300-nm CO_2 laser was approved by the US Food and Drug Administration (FDA) and recently introduced in 2010 for both hard and soft tissue surgery (SOLEA, Convergence Dental, Inc., USA). The 9,300-nm wavelength is produced by using an isotope $^{12}C^{18}O_2$ gas molecule instead of the normal $^{12}C^{16}O_2$ molecule. Both ^{18}O and ^{16}O are naturally stable CO_2 molecules. Because ^{18}O is heavier, with extra two neutrons, the frequency and energy level of molecular vibration is different from ^{16}O [13].

Optical properties and laser parameters

Clinical applications with CO_2 lasers rely on understanding of optical properties (how tissues act on lasers) and laser parameters (how lasers act on tissues). Different isotopes contained in the CO_2 molecule generate different output wavelengths of CO_2 lasers. A CO_2 laser generates a beam of infrared light with the wavelength bands primarily on 9,300 nm, 9,600 nm, 10,300 nm, and 10,600 nm. The CO_2 wavelengths lie in the far infrared of the electromagnetic spectrum. The main chromophores are water and hydroxyapatite. Figure 1 shows the absorption spectra in log scale of common biological materials by common dental lasers.

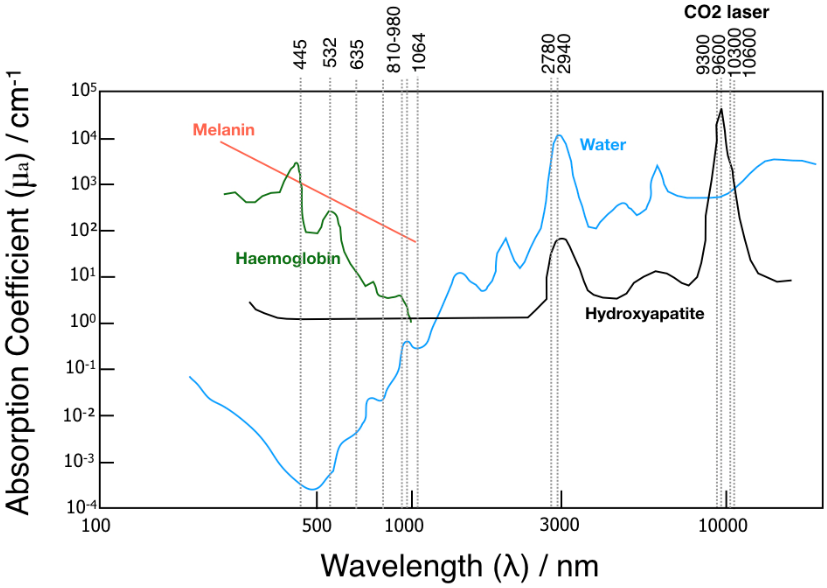

Figure 1 Absorption spectra (log scale) of some biological materials and laser wavelength (adapted from [15]**)**

The absorption coefficient of all CO_2 wavelengths to water are very similar, as shown in Figure 1. The 10,600-nm CO_2 wavelength has an absorption coefficient to water of approximately 6.6×10^2 cm^{-1}. This gives an absorption or penetration depth (reciprocal of absorption coefficient) of 15 μm in water. Because soft tissue contains over 70% water, this makes CO_2 lasers the suitable wavelengths for soft tissue surgery. The CO_2 wavelengths have a higher absorption coefficient to hydroxyapatite than to water. Among the four CO_2 laser wavelengths, 9,600 nm has the best absorption coefficient to hydroxyapatite, which is the main component of enamel and dentine. Table 2 is a summary of the absorption coefficients and depth of 9,300 nm, 9,600 nm, 10,300 nm, and 10,600 nm CO_2 laser wavelengths in enamel and dentine [16]. The absorption depth in enamel and dentine with 9,300 nm and 9,600 nm wavelengths are shallower than with 10,300 nm and 10,600 nm wavelengths.

	Wavelength of CO_2 Laser (nm)			
	9,300	9,600	10,300	10,600
Absorption coefficient of enamel (cm^{-1}) [17]	5500	8000	1125	825
Absorption depth of enamel (µm) [17]	2.0	1.0	9.0	12.0
Absorption coefficient of dentine (cm^{-1}) [16]	5000	6500	1200	813
Absorption depth of dentine (µm) [16]	2.0	1.5	8.3	12.0

Table 2 Absorption coefficient and depth of enamel/dentine with carbon dioxide lasers

Variations in laser parameters acting on enamel and dentine produce different thermal effects. Early studies investigated the interaction of CO_2 wavelengths and laser parameters on surface temperature increase, surface melting, morphological surface changes, and chemical changes on the enamel surface [18-21]. At 4-6 J/cm² and 100 µsec pulse, a temperature increase of 590-770ºC (Figure 4) with 10,300 nm and 10,600 nm wavelengths is expected to reduce the carbonate, acid phosphate, and protein content of enamel (Table 3). After shortening the pulse duration to 50 µsec, the melting effect was observed with a 10,600 nm wavelength at 5 J/cm², suggesting a temperature increase over 1000ºC (Figure 3). However, enamel ablation without carbonisation was reported with a pulse duration between 10-20 µsec at 30 J/cm² [22]. For 9,300 nm and 9,600 nm wavelengths with 4-6 J/cm² and a 100 µsec pulse, the temperature increase (720-1150ºC) is higher than for 10,300 nm and 10,600 nm wavelengths due to the higher absorption coefficient. This temperature rise correlates with the observed surface melting on enamel (Figure 2). These early studies showed how a combination of the fluence and pulse duration of CO_2 lasers acts on different enamel surface changes.

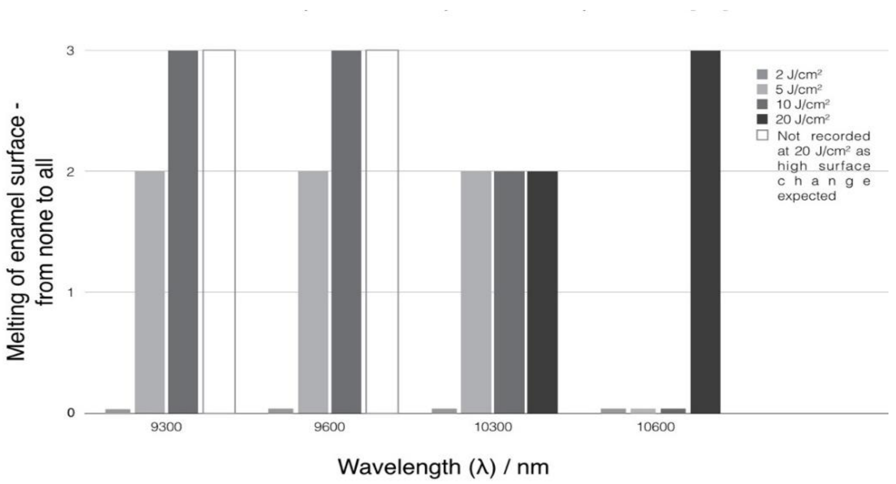

Figure 2 Effect on enamel by CO_2 lasers according to wavelength and influence.
Irradiation parameters: 25 CO_2 laser pulses at 100 μs, data adapted from [18].
Melting of enamel surface
0 - No surface melting
1 - Some surface melting, no crystal fusion
2 - Some surface melting with crystal fusion
3 - General surface melting with crystal fusion

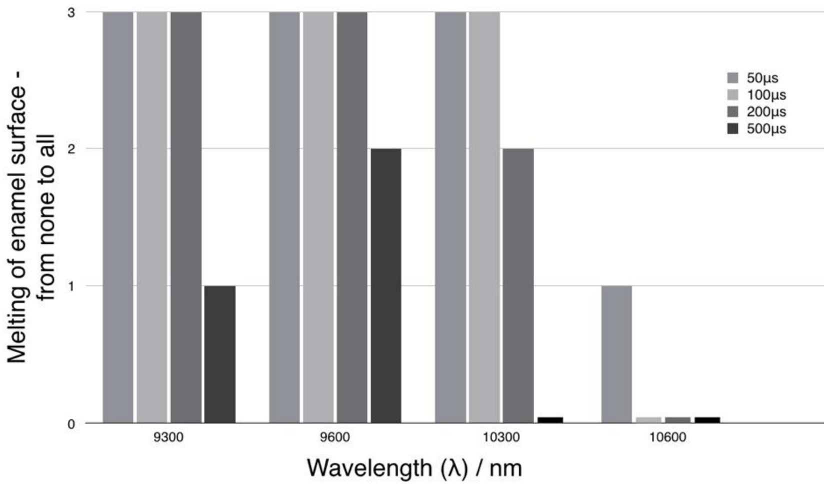

Figure 3 Effect on enamel by CO_2 lasers according to wavelength and pulse duration

Irradiation parameters: 25 CO_2 laser pulses at 5 μs, data adapted from [18].
Melting of enamel surface
0 - No surface melting
1 - Some surface melting, no crystal fusion
2 - Some surface melting with crystal fusion
3 - General surface melting with crystal fusion

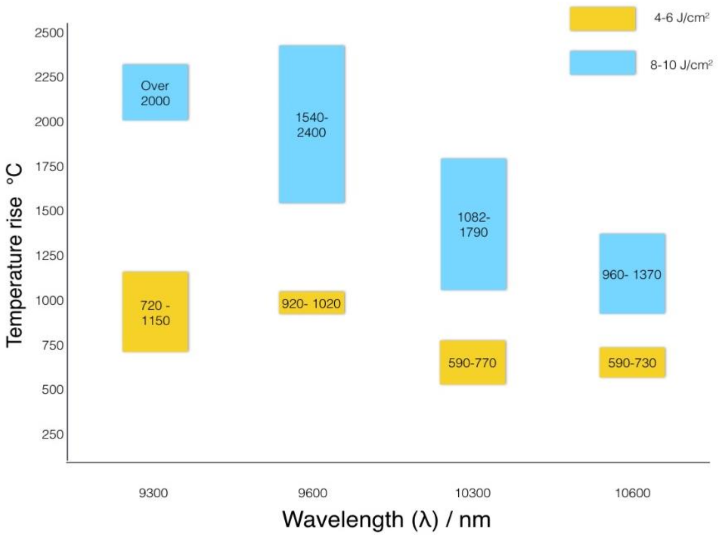

Figure 4 Temperature rise of enamel after irradiation with CO_2 lasers. Irradiation parameters: Single pulse of CO_2 wavelengths with 4-6 J/cm^2 and 8-10 J/cm^2 at 100 μs, data adapted from [20, 21]

Temperature	Chemical and morphological changes in enamel during heating in furnace
Above 1100ºC	1225ºC β-$Ca_3(PO_4)_2$ converted to α'-$Ca_3(PO_4)_2$, 1250ºC $Ca_4(PO_4)_2O$ melting 1450ºC disproportionate to α'-$Ca_3(PO_4)_2$ 1600ºC α'-$Ca_3(PO_4)_2$ and $Ca_4(PO_4)_2O$ melts. Conversion of OH^- to O^{2-}
650-1100ºC	Recrystallization, crystal growth of β-$Ca_3(PO_4)_2$ formed in tooth enamel Decrease in OH^- and conversion of OH^- to O^{2-} Loss of H_2O and CO_3^{2-} and loss of trapped CO_2 + NCO^-
110-650ºC	Decomposition and denaturation of proteins Formation of pyrophosphate P_2O_7 from acid phosphate HPO_4^{2-} CO_3^{2-} loss (-66%)

Table 3 Chemical and morphological changes of enamel at different temperatures (adapted from Fowler & Kuroda 1986 [21])

Currently, the parameters for a 9,300-nm CO_2 laser (SOLEA) operate uniquely in dental hard tissue ablation and differently from 10,600-nm CO_2 lasers in soft tissue ablation. According to manufacturer specifications, the laser operates between 1 μsec to 130 μsec with a maximum pulse energy of 42.5 mJ, 1,019 Hz at 130 μsec. These parameters are not disclosed on the control panel. The parameters were measured using a PowerMax Pro 150F HD-50mW-150W fan-cooled sensor and LabMax-Pro SSIM Laser Power Meter. For adult hard tissue mode, Figure 5 shows the pulses measured (from the authors' unpublished data). Fifty-three pulses (30 W-106 W) are delivered in 43 msec followed by a pulse pause of 13 msec. The frequency is calculated as 950 pulses per second.

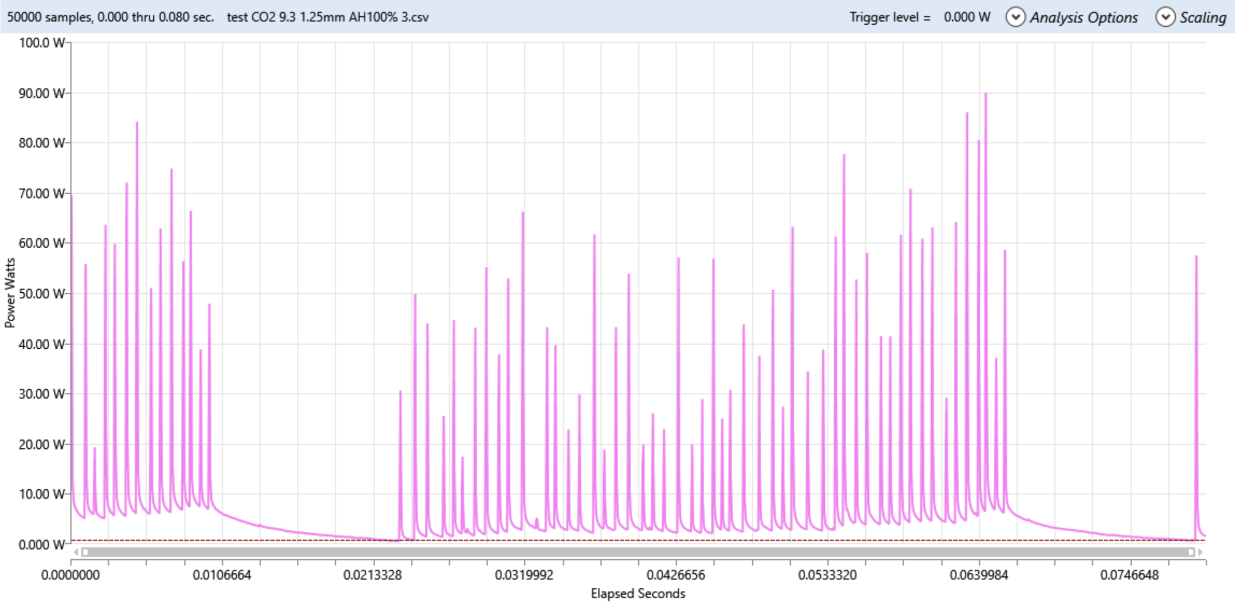

Figure 5 Adult hard tissue mode at 100% power 9,300-nm SOLEA laser

The laser operates differently under soft tissue mode. For example, at 0.75-mm spot size, the frequency is constant at 187 Hz, while the peak power is 150 W for 10% power. The peak power is 260 W from 20% to 100% power (Figure 6). Pulse duration increases from 16.5 μsec at 10% power to 133 μsec at 100% power (Figure 7) (from the authors' unpublished data).

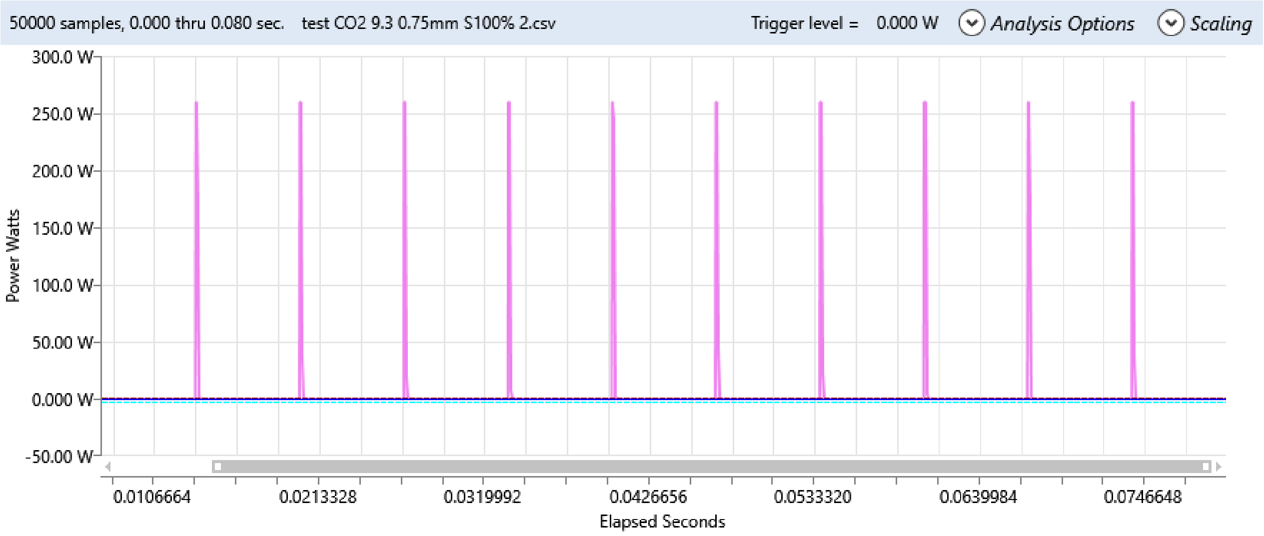

Figure 6 A 9,300-nm CO_2 laser in soft tissue mode with spot size 0.75 mm and 100% power (measured peak power 260 W, repetition rate 187 Hz)

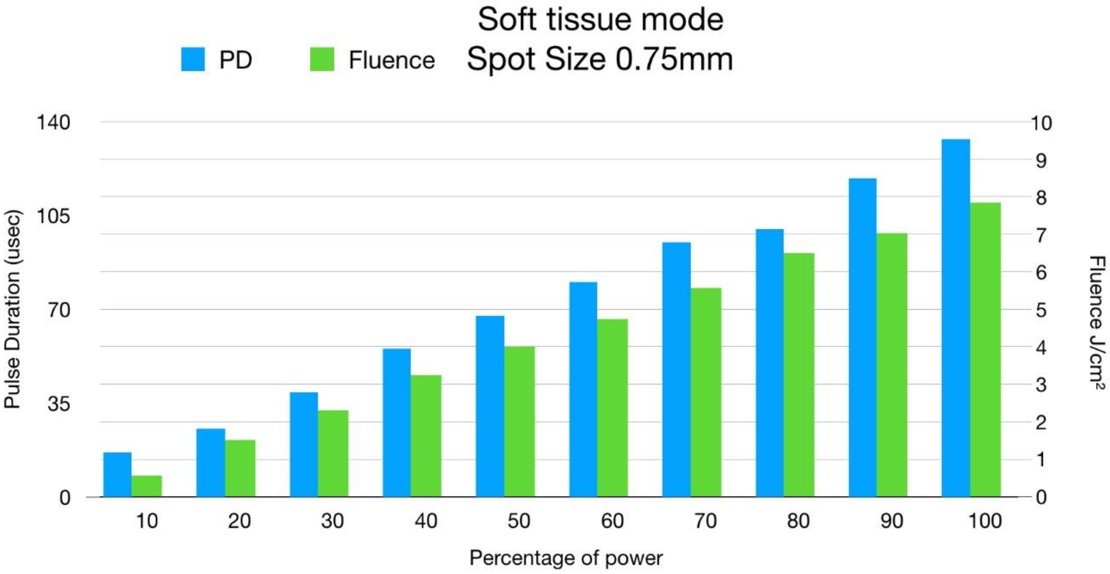

Figure 7 Pulse duration and influence in relation to the power percentage of 9,300-nm CO_2 laser in soft tissue mode with a repetition rate of 187 Hz

Laser interactions with dental hard tissue and their clinical applications

Although many laboratory and clinical studies have been conducted with CO_2 lasers on dental hard tissue, only recently could these findings be clinically implemented because there is currently only one 9,30- nm CO_2 dental laser approved for hard tissue application by the FDA. Laser interactions with dental hard tissue fall into three major categories, namely 1) interaction with the mineral, 2) interaction with the protein and lipid, and 3) interaction with the water [23]. CO_2 lasers can be used in tooth ablation and caries prevention. For ablation, the fluence must be above the ablation threshold, the point above which sufficient energy has been added to the surface in a short enough period of time to cause expansion and/or vaporisation of the tissue. In the case of CO_2 lasers, absorption in both the mineral and water will occur with some melting and vaporisation of the mineral at around 1,000ºC and above, as well as heating and expansion of subsurface water. It has been reported that the use of a 9,300-nm CO_2 laser with a fluence of 9 to 42 Jcm^{-2} at a higher repetition rate (300 Hz) can ablate enamel and dentine effectively [24].

The role of CO_2 lasers in dental caries prevention has been explored since the 1960s. For caries prevention purposes, it is likely that the most effective wavelengths are those that are most strongly absorbed by the mineral of dental hard tissues. The CO_2 laser wavelengths of 9,300 nm, 9,600 nm, 10,300 nm, and 10,600 nm overlap with the strong phosphate absorption bands of the mineral. To prevent dental caries, the laser light must alter the composition or solubility of the dental substrate and the energy must be strongly absorbed and efficiently converted to heat without damage to underlying or surrounding tissues [25]. Studies on the effects of CO_2 lasers have focused on increasing the resistance to caries by reducing the rate of subsurface enamel and dentine demineralization [26, 27]. A greater depth of carbonate loss in enamel by a 10,600-nm CO_2 laser was observed compared to that by a 9,600-nm CO_2 laser [17]. Featherstone et al. reported that using a pulsed 9,600-nm CO_2 laser produced an 84% inhibition of demineralization in an intra-oral crossover study [23]. Furthermore, some studies have combined the effects of lasers with fluoride [28, 29]. In an *in vivo* study, Rechmann et al. showed that occlusal fissures irradiated by a 9,600-nm CO_2 laser followed by fluoride varnish application twice a year are more resistant to caries than fissures without irradiation [30]. Another study using a 9,300-nm CO_2 laser showed that mineral loss was reduced by 55% compared to fluoride application [31]. However, it was reported that there was no increase in acid resistance in dentine when using 9,300-nm CO_2 lasers [32]. Further studies are needed to determine the clinical application of CO_2 lasers in caries prevention because there are vast variations in the parameters used.

Currently, the 9,300-nm CO_2 laser (SOLEA) is the only CO_2 laser on the market that is FDA approved for dental hard tissue ablation. Dental hard tissue ablation is possible with minimal collateral tooth and pulpal damage [33-37]. Power, pulse duration, and frequency as adjustable parameters were discarded from the panel. They were replaced by spot size, power percentage, and water percentage. This makes the unit user friendly for operators without much understanding of laser parameters. The novel idea of using a digital rheostat foot pedal changes the percentage of power, thereby controlling the speed of ablation. Dentists are familiar with using a foot pedal to control turbine speed. The presence of a continuous water spray is essential to prevent a rise in temperature and the possibility of irreversible damage to the pulp [38]. Clinical application of CO_2 lasers in preventive and restorative dentistry may be closer to being a reality [13].

Laser interactions with oral soft tissues and their clinical applications

Oral soft tissues are largely composed of water, which absorbs lasers, such as CO_2 lasers, well in the mid-infrared (erbium lasers) and far-infrared spectra. Penetration depth in water by CO_2 laser energy is in the region of 10 µm. This results in tissue interaction predominantly on the surface of soft tissue at 50 µm. Volumetric expansion from liquid to steam is in the ratio of 1:1,600. This rapid expansion results in vaporisation (ablation) of the soft tissue. Rapid thermal conduction of tissue around the vaporised zone results in protein denaturation, desiccation and shrinkage, and carbonisation of tissue.

There are many advantages to performing soft tissue surgery with a 10,600-nm CO_2 laser. Capillaries are effectively sealed and coagulated during ablation in surgical sites, resulting in minimal bleeding with a clearly visible operating field, which may reduce operation time. The laser surgical wound heals by secondary intention. The surgical site is decontaminated by laser energy with a low chance of bacteraemia and less suturing need. In all laser wounds beyond the ablation and coagulation zones, there is a zone of photobiomodulation, which improves wound healing compared to scalpel and electrosurgery. Hyaluronic acid is a chemical which plays a key role in wound repair. A higher level of hyaluronic acid is found in a CO_2 laser wound compared to a scalpel wound. Reduction in post-operative swelling, pain, and scarring is achieved with the appropriate laser parameters and clinical technique. Patient acceptance is high, with less post-operative discomfort. Hence, the CO_2 laser is first used in oral surgery and in implant surgery, such as for excision, incision of soft tissues, premalignant lesion removal, and pre-prosthetic surgical procedures [39, 40]. In orthodontics, a CO_2 laser can be used to perform frenectomies in children and teenagers [41] and removal of hyperplastic tissues around orthodontic brackets [33]. Gingivectomies, gingivoplasties [42], de-epithelialisation for periodontal tissue regeneration [43], soft tissue crown lengthening, and cosmetic gingival recontouring [44] are periodontal procedures for which a CO_2 laser can be used. Furthermore, CO_2 lasers can be used for mucoceles removal in soft tissues [45]. Premalignant lesions such as leukoplakia and oral lichen planus may be treated by excision for biopsy or ablation [46]. CO_2 lasers have also been used for removal of hyperplastic soft tissues and soft tissue management around the implant in cases of peri-implantitis and implant uncovering of submerged healed implants [47]. In addition, CO_2 lasers can be used for tissue removal layer by layer (i.e. peeling) in melanin depigmentation of gingiva and vaporisation of vascular lesions. The advanced laser parameters in the 9,300 nm SOLEA CO_2 laser will give the operator even greater control in soft tissue surgery [13].

Conclusion

The 10,600-nm CO_2 laser is widely accepted for soft tissue surgery applications. Although CO_2 lasers have been studied extensively in caries prevention, they have not been applied in clinical practice. The optical properties of 9,300-nm and 9,600-nm CO_2 wavelengths are suitable for dental hard tissue treatment. Technological advancements in software and laser parameters will aid in new clinical application and technique development. CO_2 lasers as hard tissue lasers will become more popular and more widely accessible to researchers and clinicians.

Conflict of Interest

The authors declare that they have no conflict of interest.

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Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

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