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Prof. Dr Norbert Gutknecht

ISLD President and Scientific Chairman

Together towards a bright future

Dear friends and colleagues,

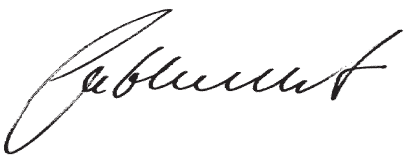
I believe that all of us dental laser users worldwide would love to see a bright future for laser dentistry. Your participation in our International Society for Laser Dentistry (ISLD), German association for laser dentistry (Deutsche Gesellschaft für Laserzahnheilkunde—DGL) and World Academy for Laser Education and Research in Dentistry (WALED) congresses, held from 6 to 8 June in Plovdiv in Bulgaria, was essential for strengthening not only the ISLD but also the participating national societies, which are constantly striving to enrich the knowledge of their members and to promote professional excellence in the use of dental lasers through research and education.

Plovdiv, the oldest city in Europe, has been designated the 2019 European Capital of Culture. It was, thus, only natural that the city, founded 4,000 years ago, had unanimously been selected as the venue for the 17th International Congress of the ISLD, the 28th annual meeting of the DGL and the 7th WALED Congress. Our Organising Chairman, Dr Georgi Tomov, his team and the entire Bulgarian Society for Laser Dentistry did a fantastic job in hosting more than 250 laser enthusiasts from around the globe in their beautiful city.

I would like to express my deepest gratitude to everyone who attended our congress in Plovdiv and joined us for an outstanding event that brought technology and culture together to create an unforgettable experience.

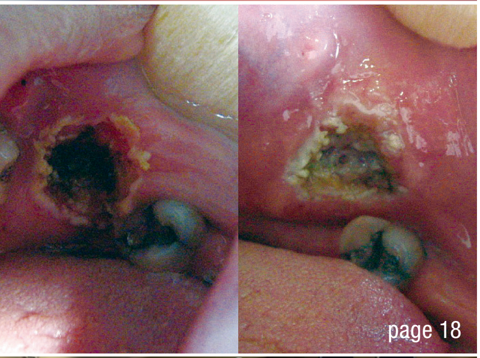
I am already looking forward to our next World Congress, to be held from 1 to 3 October 2020 in Cairo in Egypt. Save the date and join us for yet another great celebration of laser art and science, helmed by the ISLD—the leading society worldwide for laser dentistry.

Yours



Prof. Dr Norbert Gutknecht


page 12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page 34

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Use of carbon dioxide lasers in dentistry

Dr Kenneth Luk, Irene Shuping Zhao, China; Prof. Norbert Gutknecht, Germany & Prof. Chun Hung Chu, China

"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) and 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, 635 and 810–980 nm), potassium titanyl phosphate lasers (532 nm, green), neodymium-doped yttrium aluminium garnet (Nd:YAG) lasers (1,064 nm), erbium lasers (2,780 and 2,940 nm) and carbon dioxide (CO_2) lasers (9,300 and 10,600 nm). Each laser wavelength has a specific thermal output and a particular tissue interaction.

Model	Manufacturer	Location
Miran	Mediclase	Tel Aviv, Israel
CYMA Dental	BISON MEDICAL	Seoul, South Korea
Surgical CO_2 laser	DOCTOR MED	Seoul, South Korea
2015 Korea fractional CO_2 laser	Daeshin Enterprise	Seoul, South Korea
DENTA 2	GPT Dental	Fairfield, Neb., USA
LightScalpel	LightScalpel	Bothell, Wash, USA
OPELASER PRO	YOSHIDA DENTAL	Tokyo, Japan
Smart US20D	DEKA	Calenzano, Italy

Table 1: Several 10,600 nm carbon dioxide lasers on the market.

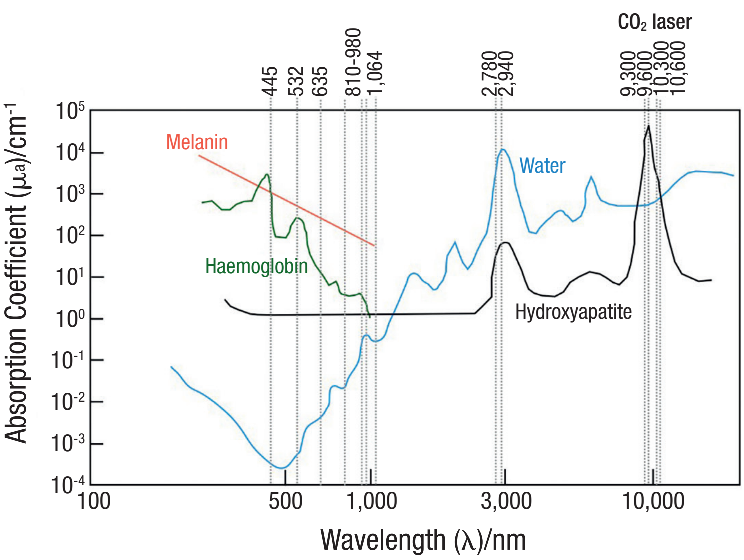

Fig. 1: Absorption spectra (log scale) of several biological materials and laser wavelengths (adapted from Zuerlein et al.[15]).

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 laser energy is well absorbed by water, it is absorbed on the surface of the soft tissue. The visible lasers (445–660 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 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 dental hard 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 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 for use in clinical dentistry. It is available in 10,600 nm on the market (Table 1).

CO_2 lasers are often used in soft-tissue surgery because their wavelengths are well absorbed by water, which makes up 70 % of biological tissue. They penetrate less than a millimetre and can produce excellent coagulation, along with a very precise cut.[7,8] 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 tissue, which contains mainly hydroxyapatite, with a melting point over 1,600 °C.

The time required results in carbonisation, melting and cracking of enamel.[9–11] The transversely excited atmospheric pressure (TEA) CO_2 laser was developed by energising a gas laser with a high-voltage electrical discharge in a gas mixture, generally above atmospheric pressure.[12] A pulsed low-energy CO_2 laser is available with very short pulse durations of a few microseconds with a high repetition rate (frequency) of over 1,000 Hz per second. These developments make CO_2 lasers suitable 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.

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 radio frequency, 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 owing 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 owing 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 production of 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] The TEA CO_2 laser has such a design. The TEA CO_2 laser can achieve

	Wavelength of CO_2 lasers (nm)			
	9,300	9,600	10,300	10,600
Absorption coefficient of enamel (cm^{-1})[17]	5,500	8,000	1,125	825
Absorption depth of enamel (µm)[17]	2.0	1.0	9.0	12.0
Absorption coefficient of dentine (cm^{-1})[16]	5,000	6,500	1,200	813
Absorption depth of dentine (µm)[16]	2.0	1.5	8.3	12.0

Table 2: Absorption coefficient and depth of carbon dioxide lasers in enamel/dentine.

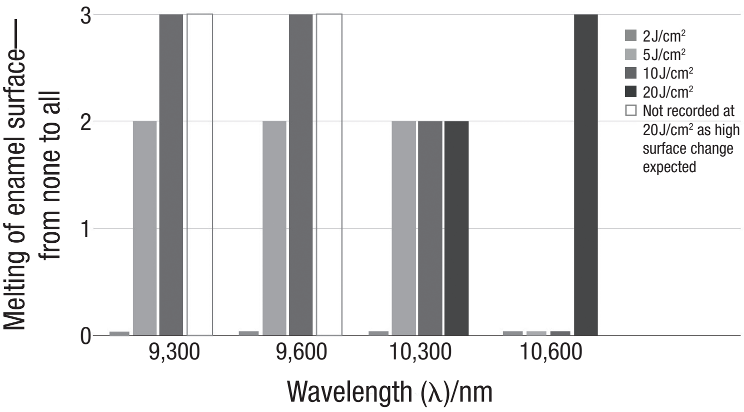

Fig. 2: Effect on enamel by carbon dioxide lasers according to wavelength and fluence. Irradiation parameters: 25 carbon dioxide laser pulses at 100 µs (data adapted from McCormack et al.[18]). Melting of enamel surface: 0 = no surface melting; 1 = some surface melting, no crystal fusion; 2 = some surface melting with crystal fusion; 3 = general surface melting with crystal fusion.

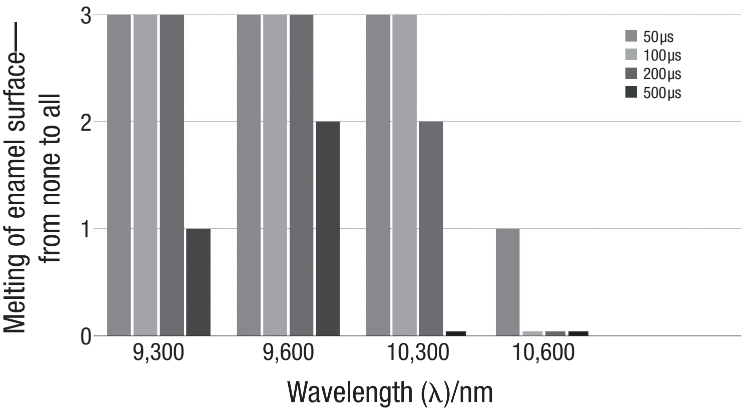

Fig. 3: Effect on enamel by carbon dioxide lasers according to wavelength and pulse duration. Irradiation parameters: 25 carbon dioxide laser pulses at 5 J/cm² (data adapted from McCormack et al.[18]). Melting of enamel surface: 0 = no surface melting; 1 = some surface melting, no crystal fusion; 2 = some surface melting with crystal fusion; 3 = general surface melting with crystal fusion.

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 U.S. Food and Drug Administration (FDA) and introduced in 2010 for both hard- and soft-tissue surgery (Solea, Convergent Dental). 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 are different from those of ^{16}O.[13]

Optical properties and laser parameters

Clinical applications with CO_2 lasers rely on understanding of optical properties (how tissue acts on laser energy) and laser parameters (how laser energy acts on tissue). 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 at 9,300; 9,600; 10,300 and 10,600 nm. The CO_2 wavelengths lie in the far-infrared electromagnetic spectrum. The main chromophores are water and hydroxyapatite. Figure 1 shows the absorption spectra in log scale of common biological materials of common dental lasers. The absorption coefficients of all CO_2 wavelengths to water are very similar. The 10,600 nm CO_2 wavelength has an absorption coefficient to water of approximately $6.6 \times 102.0\,cm^{-1}$. 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 laser wavelengths suitable 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 provides a summary of the absorption coefficients and depth of 9,300; 9,600; 10,300 and 10,600 nm CO_2 laser wavelengths in enamel and dentine.[16] The absorption depths in enamel and dentine of 9,300 and 9,600 nm wavelengths are shallower than for 10,300 and 10,600 nm wavelengths. 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] These early studies showed how a combination of the fluence and pulse duration of CO_2 lasers acts on different enamel surface changes (Figs. 2–4). At 4–6 J/cm² and a 100 µs pulse, a temperature increase of 590–770 °C (Fig. 4) with 10,300 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 µs, the melting effect was observed with a 10,600 nm wavelength at 5 J/cm², suggesting a temperature increase of over 1,000 °C (Fig. 3). However, enamel ablation without carbonisation was reported with a pulse duration of between 10 and 20 µs at 30 J/cm².[22] For 9,300 and 9,600 nm wavelengths with 4–6 J/cm² and a 100 µs pulse, the temperature increase (720–1,150 °C) is higher than for 10,300 and 10,600 nm wavelengths owing to the higher absorption coefficient. This rise in temperature correlated with the observed surface melting on enamel (Fig. 2).

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 the manufacturer's specifications, the laser operates between 1 and 130 µs, with a maximum pulse energy of 42.5 mJ and 1,019 Hz at 130 µs. These parameters are not displayed on the control panel. The parameters were measured using a PowerMax-Pro 150F HD, 50 mW, 150 W fan-cooled sensor and LabMax-Pro SSIM Laser Power Meter (both Coherent). For adult hard-tissue mode, Figure 5 shows the pulses measured (from the authors' unpublished data). Fifty-three pulses (30–106 W) are delivered in 43 µs, followed by a pulse pause of 13 µs. The frequency is calculated as 950 pulses per second. The laser operates differently in 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 at 10 % power. The peak power is 260 W at 20–100 % power (Fig. 6). Pulse duration increases from 16.5 µs at 10 % power to 133 µs at 100 % power (from the authors' unpublished data; Fig. 7).

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 9,300 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 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 1,000 °C 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 9–42 J/cm² 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 tissue. The CO_2 laser wavelengths of 9,300; 9,600; 10,300 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 the underlying or surrounding tissue.[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 demineralisation.[26,27] A greater depth of carbonate loss in enamel with a 10,600 nm CO_2 laser was observed compared with that with a 9,600 nm CO_2 laser.[17] Featherstone and Frieda reported that using a pulsed 9,600 nm CO_2 laser produced an 84 % inhibition of demineralisation in an intraoral cross-over study.[23] Furthermore, some studies have combined the effects of lasers with those of fluoride.[28,29] In an *in vivo* study, Rechmann et al. showed that occlusal fissures irradiated with a 9,600 nm CO_2 laser followed by fluoride varnish application twice a year were more resistant to caries than fissures that did not undergo irradiation.[30] Another study using a 9,300 nm CO_2

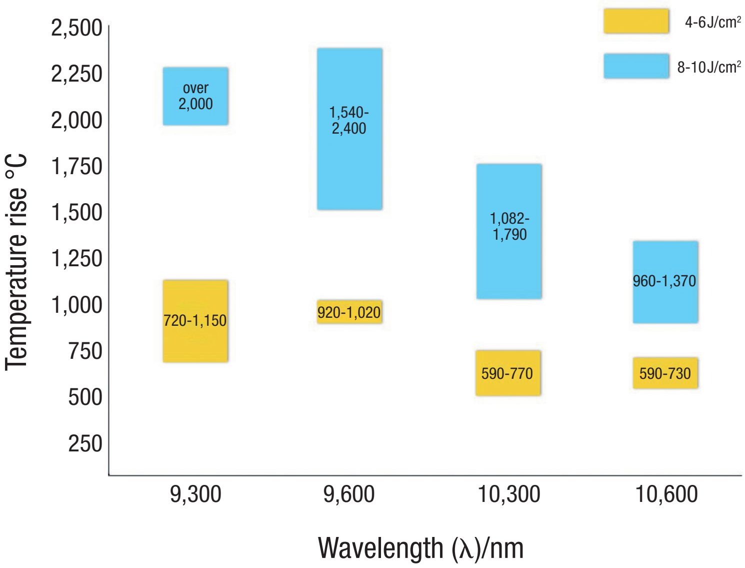

Fig. 4: Temperature rise of enamel after irradiation with carbon dioxide lasers. Irradiation parameters: single pulse of carbon dioxide wavelengths of 4–6 J/cm² and 8–10 J/cm² at 100 µs (data adapted from Fried et al. and Fowler & Kuroda[20,21]).

Temperature	Chemical and morphological changes in enamel during heating in furnace
Above 1,100 °C	1,225 °C β-$Ca_3(PO_4)_2$ converted to α′-$Ca_3(PO_4)_2$, 1,250 °C $Ca_4(PO_4)_2O$ melting 1,450 °C disproportionate to α′-$Ca_3(PO_4)_2$ 1,600 °C α′-$Ca_3(PO_4)_2$ and $Ca_4(PO_4)_2O$ melts. Conversion of OH^- to O^{2-}
650–1,100 °C	Recrystallisation, 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^-
110–650 °C	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 and Kuroda 1986)[21].