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Carbon dioxide laser in dental caries prevention

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CO_2 laser; Caries prevention; Enamel; Dentin; Fluoride

Summary *Objectives*. To describe CO_2 laser characteristics and to review the literature regarding its effects on caries inhibition in enamel and dentin. Another aim of this review is to discuss the effects of CO_2 laser in combination with fluoride.

Data and sources. The literature was searched for review and original research papers relating CO_2 laser characteristics, CO_2 laser effects on enamel and dentin, use of CO_2 laser in dental caries prevention and the effects of CO_2 laser in combination with fluoride. The articles have been selected using Medline and manual tracing of references cited in key papers otherwise not elicited.

Study selection. Dental studies pertinent to key aspects of review, and those that focus on CO_2 laser.

Conclusions. Irradiation of dental enamel by specific wavelengths and fluencies of CO_2 laser alters the hydroxyapatite crystals reducing the acid reactivity of the mineral; CO_2 laser irradiation in combination with fluoride treatment is more effective in inhibiting caries-like lesions than CO_2 laser irradiation or fluoride alone; When laser and fluoride are combined, it is possible to reduce laser energy density and fluoride levels; If this laser technology becomes available at a reasonable cost and the results can be applied in clinical practice, there will be a promising future for this laser in caries prevention.

Introduction

A significant decline in dental caries has been observed over the last few decades, not only in industrialized countries,[1] but also in developing ones.[2] However, the manifestation of this disease is still high in some individuals. Epidemiological studies have shown that a low percentage of

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children have a high number of dental caries.[3,4] In the high caries risk situations cited above, the development of new methods to prevent dental caries is extremely important to control the disease completely.

Since the development of a ruby crystal laser in 1960 by Maiman,[5] different lasers have been studied for use in dentistry. Many studies were performed to examine the effects of lasers on hard dental substrates with several different applications. Stern and Sognnaes[6] carried out the first study, which demonstrated that dental enamel exposure to ruby laser irradiation increased its acid resistance. Thus, initially, this kind of laser technology was used to remove carious enamel and dentin. Subsequently, lasers of various types were introduced, and the number of potential applications in dentistry increased.[7]

During the last 35 years, several studies, using different kinds of lasers, have demonstrated the potential of laser pre-treatment of enamel or tooth roots in inhibiting subsequent artificial caries-like lesions in the laboratory.[8–21] However, the wavelengths (λ) of the Argon lasers ($\lambda = 488$–514 nm) and Nd:YAG lasers ($\lambda = 1064$ nm) seem to fail to be effectively absorbed by enamel.[7] On the other hand, studies have been carried out to evaluate the effect of CO_2 laser on enamel and dentin structures, showing its absorption by dental tissues to be high.[22,23]

This laser was developed in 1964 by Patel et al.,[24] and it seems to be the most appropriate for preventing dental caries. Therefore, the aim of this article is to describe the characteristics of the CO_2 laser and to review the literature with regard to its effects on caries inhibition in enamel and dentin. Another aim of this review is to discuss the effects of the CO_2 laser in combination with fluoride.

Laser principles and definition of terms

The word 'laser' is an acronym for Light Amplification by Stimulated Emission of Radiation.[7] Lasers are devices that generate or amplify light and cover radiation at wavelengths ranging from infrared range to ultraviolet and even soft X-ray range. In general, a laser device consists of: (1) a laser medium like atoms, molecules, ions or semiconductor crystals; (2) a pumping process to excite these atoms (molecules, etc.) into higher energy levels; and (3) an optical resonator (laser cavity) that is composed of suitable optical feedback elements that allow the beam of radiation to pass through the laser medium.[7] In laser therapy several factors related to exposure need to be understood and considered. Thus the following definitions, frequently used in laser research publications, will help clarify the terminology used in this review.

- Wavelength is the distance between two successive wave crests (curved tops or ridges of an oscillating wave).
- Watt is a metric unit of measurement of the intensity of power that gives rise to the production of energy at the rate of 1 J/s.
- Joule is a measurement of energy that is equivalent to 0.239 cal.
- Energy density is the total amount of energy per unit surface area and is expressed in joules per square centimeter (J/cm^2).
- Hertz is a measure of frequency.

Laser characteristics

A carbon dioxide laser is one of the most popular and useful sources of coherent electromagnetic waves in the infrared spectrum. This is due to the several ways in which the laser operates (high voltage power supply in continuous wave (cw) or pulsed operation; emission of laser lines in regular, hot or sequential vibrational bands of CO_2 laser molecules) and the several orders of magnitude range of possible laser powers (from milliWatts to GigaWatts) that permit laser application in science, medicine and technology.[25] This laser uses a mixture of CO_2, N_2 and He, with CO_2 being the active laser medium (molecules that will collide with nitrogen molecules and will give out energy). Carbon dioxide lasers present over a hundred different emission laser lines with wavelengths ranging from 9 to 11 μm. The most powerful laser lines are centered at 9.3, 9.6, 10.3 and 10.6 μm, respectively. The 10.6 μm laser line is the strongest one, and most of the commercially available medical CO_2 lasers operate only at this wavelength. However, this kind of laser can be adapted to operate at the other wavelengths by various dispersive and non-dispersive methods and suppliers such as prisms, gratings (tool of choice when there is a need to separate light of different wavelengths with high resolution) and windows.[26]

For dentistry applications, all of the CO_2 lasers work in a non-contact mode and can be operated in cw, or pulsed beam.[7] The most important parameter in the way light affects the tissue is the laser line wavelength, but power and time exposure are also important.[27,28] The development of hollow waveguide technology with tubes of small diameter, a very short focal distance and tiny hand pieces, put an end to the problems of laser radiation transmission and access to difficult areas of the mouth, as well as preventing accidental irradiation of non-target tissues.[29]

The most efficient CO_2 laser for hard tissue is the TEA laser. The name TEA is an acronym for transversely excited atmospheric pressure laser. This CO_2 gas laser uses a transverse flow of gas and operates at higher pressures than other gas lasers, generally near atmospheric pressure. The laser is operated in a pulsed regime of a few Hz of repetition rate and pulses of 0.1–0.2 μs duration, resulting in peak powers in the GigaWatts range.[30]

Laser-tissue interactions

Laser energy (power $\times$ time) interacts with target substances according to the individual wavelengths. The different wavelengths have several degrees of relative absorption into the various components of hard and soft tissues. Laser-tissue interaction is also controlled by other irradiation parameters such as continuous or pulsed emission, repetition rate, pulse duration, pulse energy, beam size and delivery method, spatial and temporal characteristics of the laser beam, and optical properties of the substrate.[30,31] Earlier researches and new observations have provided parameters on which scientists and dentists can base the choice of appropriate wavelengths and other laser conditions to perform the desired tasks.[31,32] When delivered to the target tissue site, the laser light can be:[28,31]

- *Reflected:* It happens when the laser light reflects off of a surface in a direct or diffuse fashion.
- *Absorbed:* The laser energy interacts with the atoms in the target tissue and is generally converted to heat.
- *Transmitted:* The energy travels directly through tissue, causing no effect. It passes into underlying tissue.
- *Scattered:* The laser energy spreads out into a larger area. If the light is scattered, it is no longer a coherent beam and it is not delivered where needed.

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.[32] Therefore, knowledge of the absorption (μ_a) and scattering (μ_s) coefficients (related to the energy absorbed per length unit) for diverse dental tissues is relevant. These coefficients have been determined and are given values with units of reciprocal centimeters (cm^{-1}). For materials with high absorption, $\mu_a > 100\ \text{cm}^{-1}$, the laser energy is absorbed within 100 μm of the surface and converted to heat.[30,31] Energy transport into the tissue is primarily due to heat conduction away from this surface, and light scattering is insignificant. This condition is representative of the interaction between dental hard substrates and CO_2 lasers.[30]

Dental enamel and dentin have weak absorption in the visible (400–700 nm) and near-infrared (1064 nm) spectrum.[30,33] Thus, the majority of the earliest studies that were carried out using near infrared or visible light lasers often applied very high irradiation intensities ($>10^7\ \text{W/cm}^2$) to generate the desired effects. The high energies used as well as the high transmission of these tissues in the visible and near infrared spectrum would be expected to result in subsurface damage to the pulp.[30]

On the other hand, regions and wavelengths where absorption is high correspond to specific components in the tissue. This condition is representative of the interaction between tooth substrates and CO_2 lasers.[30] Table 1 summarizes the absorption and scattering coefficients and reflectance percentage of human enamel and dentin for the CO_2 laser wavelengths.

Carbon dioxide laser energy weakens rapidly in most tissues because it is absorbed by water

Table 1 Approximate absorption and scattering coefficients and reflectance for dental enamel and dentin.

CO_2 wavelength (μm)	Absorption coefficient (cm^{-1})		Scattering coefficient (cm^{-1})		Reflectance (%)	
	Enamel	Dentin	Enamel	Dentin	Enamel	Dentin
9.3	5500	5000	Insignificant	Insignificant	37.7	8.6
9.6	8000	6500	Insignificant	Insignificant	49.4	16.7
10.3	1125	1200	Insignificant	Insignificant	15.8	10.3
10.6	825	800	Insignificant	Insignificant	13.2	8.8

Data from Refs. 22,23,31.

regardless of tissue color.[28,29] It is well absorbed by all biological tissues. This means that it is highly absorbed in oral mucosa, which is more than 90% water.[29] For dental enamel, the absorption coefficient is extremely high at 9.6 μm. This is due to the fact that the carbon dioxide laser produces radiation in the infrared region that coincides closely with some of the apatite absorption bands, mainly phosphate and carbonate group absorption bands.[16,17,32,33] Conventional CO_2 lasers used in medicine and dentistry emit light at 10.6 μm, which is also strongly absorbed by the mineral. However, the absorption of the wavelengths 9.3 and 9.6 μm is an order of magnitude higher than that for the conventional 10.6 μm CO_2 laser. The implications are that if there is an application that requires efficient and short heating of the mineral, (like for dental caries prevention using laser technology) 9.3 and 9.6 μm would be the preferred wavelengths.[16,22,23,32–34] To produce similar caries-inhibitory effects using a 9.6 and 10.6 μm, a 14-fold increase in the energy density is necessary when the second wavelength is used.[16]

In most studies using the cw CO_2 lasers, typical interaction times of 50 ms to 2 s were used. These interaction times are much longer than the thermal relaxation time of enamel (necessary time for cooling of the substrate), which is 100 μs.[30] The axial thermal relaxation time (T_r) of enamel was calculated to be approximately 60 μs for a 10 μm thermal gradient length and absorption coefficient of 1000 cm^{-1}. For those long interaction times, a large fraction of the absorbed laser energy is conducted away from the enamel surface into the interior of the tooth during the laser radiation, resulting in inefficient surface heating and possible pulp damage. In this way, the use of cw CO_2 laser irradiation for caries prevention is normally less effective and more dangerous than the use of pulsed CO_2 lasers.

Thus, pulsed lasers provide a way of increasing the peak power density while keeping the pulse energy density at low levels (hundreds of mJ/cm^2), thereby minimizing the cumulative energy deposition.[17,30] This means that changes such as fusion, melting, carbonate loss and re-crystallization of enamel crystals can be confined to a thin surface region without affecting the underlying dentin or pulp. The energy deposited at pulse durations shorter than T_r is 'thermally confined' to a thin layer at the enamel surface. On the other hand, pulse durations much longer than T_r result in ablation, which is not a desirable laser effect when caries prevention is intended.

With respect to the optimum number of pulses, Kantorowitz et al.[17] found that the best inhibitory effect of a TEA CO_2 laser on caries-like lesion development was obtained when 25 pulses of 0.1–0.2 μs were used.

In a separate study, considerable surface damage following laser irradiation over 200 mJ/pulse at a 9.6 μm wavelength was observed by scanning electron microscopy (SEM). The surface damage apparently was detrimental and provided less resistance to the acid challenge.[35] This pattern is consistent with the view that there is a point at which a further increase in the energy density of pulses significantly reduces the inhibition of caries progression. In the same way, an increase in the number of pulses can also induce an undesirable cumulative energy deposition, a consequent temperature elevation and possible pulp damage.[16,17]

In conclusion, in order to prevent dental caries it is more appropriate to use 9.6 μm CO_2 lasers, with pulsed operation, low energies (hundreds of mJ) and pulses of 100 μs or less. The total energy deposition would be of the order of a few Joules. These conditions are normally obtained with TEA CO_2 lasers working at a low Hz repetition rate, pulses of 0.1–0.2 μs, and GigaWatts peak powers. Another alternative, not yet explored, is the use of waveguide CO_2 lasers, operating at high repetition rates (kHz), and pulses in the 100 μs duration and low peak powers (100 W).[36] The advantage would be simplification of the technology and low cost of this system compared to the TEA CO_2 laser system, which has a more complex configuration. TEA lasers present a different source of supply and optic cavity and due to these differences it is more expensive and difficult to operate.

CO_2 laser in dental caries prevention

Carbon dioxide, Nd:YAG, Ho:YAG and Argon lasers have become more popular among dentists after being approved by the Food and Drug Administration for use on soft-tissue.[30] The Er:YAG laser was the first laser which was approved by FDA for limited hard-tissue procedures in 1997.[17] One potential application of dental lasers is preventive laser treatment of dental hard substrates to increase their resistance to caries. The role of CO_2 lasers in dental caries prevention has been explored since the 1960s. These studies used different types of CO_2 lasers: cw and pulsed lasers. Research on the effects of CO_2 lasers have focused on increasing the resistance to caries by reducing the rate of subsurface enamel and dentin demineralisation.[11–13,16–19,21,37–43] Furthermore, some studies have combined the effects of lasers with

Table 2 Wavelength, energy density and percentage inhibition of enamel caries by CO_2 laser in combination or not in combination with fluoride.

Author	Year	Wavelength	Beam	Energy density (J/cm^2)	With fluoride	Percentage inhibition
Nelson et al.[60]	1986	9.3	Pulsed	50	No	50
Nelson et al.[11]	1987	9.3	Pulsed	50	No	50
Kantorowitz et al.[17]	1998	10.6	Pulsed	12 per pulse	No	87
Featherstone et al.[16]	1998	9.6	Pulsed	2.5 per pulse	No	70
Phan et al.[48]	1999	9.6	Pulsed	1 per pulse	Yes	87
Young et al.[20]	2000	9.6	Pulsed	6.1	No	50
Hsu et al.[21]	2000	10.6	Pulsed	0.3 per pulse	No	98
Hsu et al.[49]	2001	10.6	Pulsed	0.3 per pulse	Yes	98
Nobre dos Santos et al.[50]	2001	9.6	Pulsed	1.5	Yes	76

fluoride.[44–51] A compilation of the main studies, which were performed to measure the CO_2 laser preventive effect on enamel with or without fluoride, is presented in Table 2. This table also gives the wavelengths and energy density used, which showed the greatest percentage of caries inhibition. For any procedure using lasers, the optical interactions between the laser light and enamel or dentin must be thoroughly understood to ensure a safe and effective treatment. However, the mechanisms of caries inhibition remain unclear. In the next two sections, we summarize the main kinds of experiments and explanations for the mechanism of caries inhibition by CO_2 lasers.

Effect of CO_2 laser on enamel

A variety of explanations have been given for the alteration of the dental enamel acid reactivity rate by treatment with CO_2 laser irradiation.

One explanation focused on the decrease in enamel permeability to chemical agents caused by physical fusion of the enamel surface microstructure.[37] However, this hypothesis seems to be unlikely, since the only study that has performed permeability experiments was carried out by Borggreven et al.[52] and they found that laser irradiation increased the permeability of enamel rather than decreasing it. These authors suggested that the reported resistance of lased enamel to subsurface demineralization might be due to chemical changes, such as the loss of organic matter and carbonate.

Another explanation has focused on the combination of reduced enamel permeability with a reduced solubility with melting, fusion and re-crystallization of enamel crystallites, sealing the enamel surface.[11,12] In addition, a less soluble compost (tetracalcium diphosphate monoxide) was identified as being a component of the melting surface and this layer presented reduced carbonate content.[12] On the other hand, a cross-sectional transmission electron microscopy examination revealed that the melting of the enamel surface was not homogeneous and usually occurred in limited areas.[53,54] Therefore, it seems that surface melting and fusion are not necessary to increase enamel resistance to demineralization,[17,35] which weakens this theory.

Stern et al.,[37] Ferreira et al.[53] and Kantola[39] carried out studies utilizing cw CO_2 lasers and demonstrated ultra-structural crystallographic effects, such as apatite crystals with a different shape and larger size, and loss of prismatic structure. The authors suggested that these effects could be responsible for the increased enamel acid resistance.

Fowler and Kuroda[41] found that the laser treatment at temperatures ranging from 100 to 650 °C may convert acid phosphate to pyrophosphate to inhibit demineralization, since Christoffersen[55] reported that pyrophosphate reduced the hydroxyapatite dissolution rate. Besides, the water content decreased and an overall reduction in total carbonate (CO_3^{2-}) content occurred. Another temperature range tested by these researchers (650–1100 °C) caused modifications in tooth enamel, which could increase or decrease the solubility depending on the Ca/P ratio and the resultant amounts of alpha-tricalcium phosphate and beta-tricalcium phosphate formed. However, treatments using temperatures over 1100 °C formed products that are expected to increase solubility in those regions that contain considerable amounts of these products.

In the same way, after producing artificial caries-like lesions in human enamel specimens heated at temperatures ranging from 100 to 600 °C, Sato[56] showed that those samples heated at temperatures below 300 °C had shallower caries lesions and a lower amount of dissolved calcium than enamel heated at temperatures ranging from

350 to 600 °C. Additionally, a temperature increase above 400 °C led to formation of pores in the enamel.

Yamamoto et al.[57] proposed a different model to explain the increase of the dental enamel resistance. The authors described a decrease in the apparent solubility of enamel after heat treatment to temperatures higher than 1200 °C. The decrease in solubility was attributed to the change in the rate of the dissolution kinetics due to the change from the more accessible dissolution site of hydroxyapatite (HAP) to a less reactive site of heat-treated apatite. The dissolution of synthetic apatites is explained by a model in which the dissolution behavior is governed by two types of dissolution sites (site Nos 1 and 2). Site No. 1 has an ion activity product (IAP) of around 10^{-121} and site No. 2 an IAP of 10^{-130}.[57] These IAPs represent the threshold IAP above which dissolution from a determined site will not occur. The reader should note that the word 'site' refers to dissolution rates which correspond to the IAP (based on hydroxyapatite stoichimetry). Heat-treated HAP has shown to possess only dissolution site No. 2, which is less soluble, while dissolution of the non-heated HAP is dominated by the more labile site No. 1.[44] Therefore, it can be speculated that heating HAP would provide a greater acid resistance. However, the dissolution studies estimate the acid resistance of the enamel surface by determining the dissolved calcium content, a phenomenon that takes place in the enamel surface and the caries process occurs also in the enamel subsurface. This fact may partly explain why the reduced dissolution rate obtained by CO_2 laser irradiation of dental enamel is higher than the caries inhibition effect observed when irradiated enamel is submitted to a cariogenic challenge. In addition, a recent study carried out by Tsai et al.,[58] showed that laser-treated enamel by a CO_2 laser tended to be more resistant to an acid challenge to a depth about 54 μm. Thus, the effect of laser irradiation is limited to the tooth surface area.

Another explanation to the caries preventive effect of the CO_2 laser is carbonate loss, which is a soluble mineral that is lost from the carbonated apatite tooth mineral during specific laser irradiation.[16,31,34] The reduced carbonate content could decrease demineralization of the substrate, because of a poorer fit of carbonate in the lattice, generating a less stable and more acid-soluble apatite phase.

Finally, the organic matrix in enamel has been shown to reduce enamel demineralization during an acid attack.[21] The laser irradiation effect, using very low energy density (0.3 J/cm^2) may heat enamel to a temperature lower than 400 °C. This effect can cause a partial decomposition of the organic matrix and could lead to a blockage of the inter- and intraprismatic spaces. Consequently, ion diffusion in enamel is compromised resulting in the reduction of enamel demineralization. This theory disagrees with the inorganic block theory, which advocates the melting of hydroxyapatite to block the enamel diffusion pathway.[21]

Therefore, it is possible to conclude that further studies are necessary to clarify the action mechanisms of lasers, which have a caries preventive effect, on dental enamel.

Effect of CO_2 laser on dentin

Since Kantola[59] showed that laser irradiation could be used to increase the dentin mineral content by preferential removal of the inherent water and protein, researchers have evaluated the susceptibility of dentin modified by various lasers systems to artificial caries-like lesion formation. However, a limited number of articles have been published concerning the changes in dentin irradiated by a CO_2 laser.

Dentin has a much higher content of water and protein than enamel, decreasing the contribution of the mineral phase and emphasizing the role of water and protein in the light absorption.[31] Like enamel, dentin absorption is low in the visible region, but the tissue scatters more than enamel,[30,31] which may have negative consequences such as subsurface vaporization, cracking and pulpal necrosis.

In dentin, the exact reasons for the caries lesion inhibition by laser treatments are also unknown. However, some hypotheses have been proposed. Kantola[59] suggested the first theory that investigated crystallographic changes in lased dentin by a cw CO_2 laser and showed that re-crystallization occurred due to laser irradiation. Simultaneously, growth in the crystal size of the crystallites was observed, and dentin of a low order of crystallinity, structurally changed in such a way as to closely resemble the crystalline structure of the hydroxyapatite of normal enamel. On the other hand, no investigation was performed in this study to verify the effects of the crystal growth on dentin resistance to demineralization.

Another action mechanism was proposed by Nelson et al.[60] who showed that fusion and melting occurred in the root dentin surface lased with a CO_2 laser at $\lambda = 9.3$ μm; these alterations were related to a caries-like lesion inhibition up to 50% with 50 J/cm^2 density energy. However, recent studies carried out by this research group have shown that the suitable energy densities for caries prevention in enamel should be lower than those used in this study.[16,31] Since dentin is more sensitive to laser irradiation than enamel, the incident energy would be even lower.

Nammour et al.[13] found good caries inhibition results in irradiated dentin. The authors used a cw CO_2 laser at $\lambda = 10.6\ \mu m$ operating at very high intensities and showed a sealed layer at the dentin surface, which delayed the diffusion of acid to the underlying sound dentin and reduced the extent of the caries lesion to a significant degree. However, in this study, laser irradiation did not completely seal the dentinal tubule lumen, thus allowing acid to diffuse through the large surface of the cracks created during the irradiation process. In addition, the energy density used was the same as that applied for caries removal, which is not appropriate for using in caries prevention, since ablation typically occurred with the first few laser pulses.

In another experiment, which used atomic analyses, the calcium (Ca) and phosphorus (P) contents of the dentin surfaces increased significantly after low-level laser irradiation, but the ratio of Ca to P was not altered and remained almost at the same level as the control (non-irradiated). The authors suggested that not only re-crystallization, but also an increase of inorganic content occurred in the laser-irradiated dentin surface, and this might be related to the increased resistance to demineralization.[18]

González et al.[42] and Kimura et al.[61] found conflicting results when they studied the CO_2 laser effect on human dentin. The first study showed[42] by SEM that the CO_2 laser effect with a wavelength of $10.6\ \mu m$ (2 W, 10 J, 0.2 s, 25 pulses) varied from charring, cratering, poring, fissuring, fracturing and cracking up to melting. It was also found that the dentinal tubules were not sealed. On the other hand, Kimura et al.[61] observed no craters or cracks, but documented many small molten and re-hardened particles on the sample surface. Some small cracks were seen in the subsurface layer, and the authors suggested that laser irradiation, using a $\lambda = 9.3\ \mu m$ and low energy density, affect the dentin surface minimally (less than $20\ \mu m$) and would be less likely to cause thermal dental pulp damage. However, these studies are not suitable for determining the optimum laser parameters for caries inhibition in dentin, because they did not investigate the effect of laser irradiation on the dentin acid resistance.

In conclusion, dentin is a less mineralized substrate than enamel and presents different characteristics. In order to modify dentin positively, the energy density necessary seems to be lower than that used for enamel. However, even the beneficial effect of dentin irradiation is not well established and its irradiation parameters still have to be determined.

CO_2 laser and fluoride on caries prevention

The decline in dental caries over the last few decades has been attributed to the widespread use of fluoride.[62] Furthermore, there is consensus that the main effect of fluoride is to interfere physically and chemically with caries development by reducing demineralization and enhancing remineralization of dental enamel.[63] Nevertheless, the fluoride effect is partial, since it cannot completely block dental caries development. Thus, the combined effects of laser and fluoride have been investigated in order to develop more effective procedures for caries prevention and control.[44–51,64–68] Some of these investigations were carried out using CO_2 lasers.[44–51]

In 1991, Featherstone et al.[43] observed that low energy laser treatment coupled with fluoride treatment entirely inhibited subsequent lesion progression in a pH-cycling model. The combination of laser irradiation and topical fluoride application decreased the enamel demineralization more than either fluoride treatment or laser treatment alone. In this study, fluoride was applied after the irradiation.

Tagomori and Morioka[65] suggested that laser-modified enamel has an enhanced uptake of acidulated phosphate fluoride and that this fluoride uptake was greater when laser treatment was performed before the fluoride treatment. This could decrease enamel demineralization by retention of fluoride. Other authors in agreement with this hypothesis are Hossain et al.[51] These studies suggested that the combination of CO_2 laser irradiation with NaF solution was more effective in preventing dental caries than CO_2 laser irradiation alone. In addition, they suggested that the retention of fluoride solution may also influence the caries inhibition effect and that laser irradiation might prolong the retention of fluoride in the enamel or dentin microstructures by increasing their adhesion to the underlying surface, keeping the effect for a longer time.

Fox et al.[44] proposed a different theory for the efficiency of this combination of CO_2 laser and fluoride. These authors treated sound enamel with cw $\lambda = 10.6\ \mu m$ radiation followed by treatment of fluoride or dodecylamine HCl or ethane-1-hydroxyl-1, 1-diphosphonic acid and observed a significant synergism between laser treatment and these chemical dissolution rate inhibitors. It was hypothesized that thermal treatment with lasers converts the carbonated hydroxyapatite of tooth enamel to a less soluble mineral, and chemical inhibitors work by a common ion effect of the fluorapatitic surface, which is more effective on the less soluble laser-modified enamel. In the same way, Meurman et al.[46] showed that it is possible to transform HAP crystals to fluorapatite (FAP) crystals instantaneously in the presence of fluoride using a CO_2 laser, and the threshold energy density needed was 38 J/cm^2. In this work, there was no investigation about the acid dissolution of the end product, because the researchers assumed that FAP is more resistant to acid attack than HAP. Additionally, the energy density used to transform HAP to FAP was very high.

Hsu et al.[47] tested the combined effects of CO_2 laser ($\lambda = 10.6\ \mu m$) irradiation and solution fluoride ion on enamel demineralization. The authors found that lased enamel had an increased acid-resistance with increasing laser energy density and, at the highest energy density of 170 J/cm^2, there was little or no lesion development in the fluoride-free dissolution medium. In the presence of fluoride, there was only modest caries development in the unlased enamel and, at an energy density 50% lower (85 J/cm^2) than the highest energy density used without fluoride, the enamel surface was found to be completely protected. Although, the combination of the methods resulted in a lower energy density being used, the effective energy density used could still be considered as being high.

Phan et al.[48] proposed that the mechanism for FAP transformation is as follows. During the fluoride gel treatment, fluoride ions diffuse through the pores between the enamel rods to deposit and form an F-veneer layer covering all the enamel rods. Following the CO_2 laser ($\lambda = 9.6\ \mu m$) irradiation, this thin F-veneer layer, along with a few additional outer micrometer of enamel surface were thermally melted and recrystallized to rearrange themselves into a new structure, the FAP mineral. This study found that the dissolution rates showed some synergistic benefits from combining fluoride and laser treatment, and that the concentrations of fluoride content incorporated into enamel structure is much higher when demineralized enamel is irradiated than when sound enamel is irradiated.

Hsu et al.[49] investigated the interaction among CO_2 laser irradiation, fluoride and the organic matrix on the human enamel demineralization. A microradiograph analysis performed after a pH-cycling procedure indicated that the combined fluoride-laser treatment led to 98.3 and 95.1% reductions in mineral loss for enamel with and without an organic matrix, respectively, when compared to sound enamel. It was demonstrated that the reduced effect (74%) of laser irradiation on enamel without an organic matrix could be compensated by the presence of fluoride during laser irradiation.

Another recent work revealed that the combination of a new $\lambda = 9.6\ \mu m$ TEA CO_2 laser and acidulated phosphate fluoride produced a significant protective effect against caries progression and caries development in smooth surfaces.[50] This research tested the ideal fluoride application time, before or after laser treatment. The best result was obtained when the fluoride was used before irradiation at an energy density of 1.5 J/cm^2 per pulse.[50]

It can be seen that there is no consensus with regard to whether the fluoride treatment should be performed before or after laser irradiation. However, all experiments associating CO_2 laser irradiation and fluoride treatment showed better results in caries prevention when compared to one single treatment. Therefore, such 'combination therapy' may be clinically effective while, at the same time, involving only moderate daily doses of both fluoride and low energy levels of laser irradiation.

Conclusions

- Irradiation of dental enamel by specific wavelengths and energy densities of CO_2 laser alters the hydroxyapatite crystals reducing the acid reactivity of the mineral;
- CO_2 laser irradiation in combination with fluoride treatment is more effective in inhibiting caries-like lesions than CO_2 laser irradiation or fluoride alone;
- When a CO_2 laser and fluoride are combined, it is possible to reduce laser energy density and fluoride levels;
- If this CO_2 laser technology becomes available at a reasonable cost and the results can be applied in clinical practice, there is a promising future for this laser in caries prevention.

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