Irradiation methods of 10,600 nm carbon dioxide for dental caries prevention

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Abstract

Objective: To investigate the parameters and irradiation techniques used for 10,600 nm carbon dioxide laser for dental caries prevention.

Methods: This study examined the 22 publications on the effects of carbon dioxide lasers on preventing caries. The parameters investigated were output power, pulse energy, frequency (for pulse laser), spot area and fluence. The techniques investigated were the mode (fixed spot or scanning motion), time and irradiation distance.

Results: Seventeen studies examined the prevention of enamel caries. The output power, pulse energy, frequency, spot area and fluence were determined and their ranges were 0.1 to 2,800 W, 0.0025 to 2,000 mJ, 8.7×10^{-8} to 0.05 cm^2, 1 to 226 Hz and 0.3 to 28.6 Jcm^{-2}, respectively. Ten studies employed scanning motion and seven employed fixed spot irradiation. The time and irradiation distance ranged from 2 to 9 s and 1 to 370 mm, respectively. Six studies examined dentin caries prevention. The output power, pulse energy, frequency, spot area and fluence ranged from 0.17 to 480 W, 1.7 to 540 mJ, 0.008 to 0.05 cm^2, 1 to 250 Hz and 0.05 to 715 Jcm^{-2} respectively. Three studies employed spot irradiation and three employed scanning motion. The time and irradiation distance range from 4 to 15 s and 5 to 198 mm, respectively. Parameters of three studies were incorrect and two studies could not be determined.

Conclusion: This review found considerable variations in the included articles' parameters and irradiation techniques reported for 10,600 nm carbon dioxide laser for caries prevention. Some studies did not provide adequate information on the parameters and the irradiation technique. A few studies reported incorrect parameters or impractical irradiation distance for clinical practice.

Introduction

Using lasers has been researched in medicine and dentistry since the 1960s. Using lasers to perform dental hard tissue preparation instead of using the drill has long been considered. Stern and Sognnaes [1] carried out the first experiment on dental hard tissue preparation with the ruby laser (680 nm wavelength) in 1964. Although the laser could vaporize enamel and dentin, there was an enormous amount of carbonization on the surface. The ruby laser was not suitable for dental structure as it was best absorbed by dark pigment and because the continuous wave mode did not allow thermal relaxation. Therefore, the appropriate wavelength for laser tissue interaction is required.

How laser acts on tissue depends on the tissue's optical property to the wavelength. Enamel and dentin mainly contain carbonated hydroxyapatite [2] and water, which are the CO_2 lasers' two chromophores. The 10,600nm wavelength is the most commonly available CO_2 laser in the market. Hydroxyapatite (8.25×10^2 cm^{-1}) has a higher absorption coefficient than water (6.6×10^2 cm^{-1}) to 10,600 nm CO_2 wavelength. Absorption depth of enamel and dentin is 12 μm, compared to the absorption depth of water, which is 15μm. The effects of enamel and dentin absorption at these depths depend on how laser energy acts on them. The laser energy depends on the laser parameters such as power, mode of operation (continuous wave or pulse mode), fluence (energy density) and dose (total energy).

The feasibility of using the 10,600nm CO_2 laser in dental hard tissue treatment has been investigated since early 80's Melcer [3]. The continuous wave mode of operation on enamel caused carbonization, melting and cracking. The development of the pulse mode allowed variations by frequency and pulse durations in milliseconds (ms) and microseconds (μs). This improved the laser's thermal control on tissue [4,5]. The dose would depend on method of irradiation (spot irradiation or scanning motion, number of times repeated irradiation). Surface cooling may influence the temperature increase on the dental surfaces.

Although the 10,600nm CO_2 laser is not suitable for cavity preparation, irradiation with low fluence can result in chemical and morphological changes [5,6]. These changes can have a caries prevention effect resulting in purifying hydroxyapatite by reducing the amount of carbonate and water [7,8], changing crystalline structure, increasing hardness [7,9] and decreasing enamel solubility [10-13]. Secondly, controlling ion diffusion results in modulating the diffusion pathway with an organic matrix [14], formulating the protective coating of apatite crystals [7,8, 15,16], inhibiting diffusion and decreasing enamel porosity [17,18]. Thirdly, resurfacing enamel may affect bacteria adhesion [19]. Furthermore, the CO_2 laser can increase fluoride uptake in enamel apatite, incorporating fluoride into apatite crystals and decrease enamel solubility [20,21,22]. However, not all fluoride with the 10,600nm CO_2 laser has the synergistic effect in demineralization resistance [23-26]. Because dentin contains a higher percentage of collagen and water than enamel, the irradiating parameters would be different from those on enamel. Melting and resolidification on root surfaces showed less mineral loss and more resistance to demineralization [27-29]. When laser and fluoride are combined, synergy occurs in preventing demineralization on dentin [24,30,31].

The above effects on caries prevention and remineralization by the 10,600nm CO_2 laser were reported in a published 2019 literature review [32,33]. However, laser parameters and irradiation techniques were not discussed. This review investigated the above aspects from the 10,600nm CO_2 laser literature review on caries prevention [32].

Methods

A total of 22 papers in this review were taken from the literature review published on “Effects of carbon dioxide lasers on preventing caries” [32]. Twenty-three sets of techniques and parameters on enamel and dentin were identified because one study [24] examined both enamel and dentin. Table 1 summarizes the 17 sets of laser parameters on enamel and Table 2 summarizes six on dentin. Output power, pulse duration, pulse energy, frequency, average power, fiber diameter, spot area and fluence were listed as laser parameters. These parameters’ relationships were included by the formulae provided. Missing parameters were calculated from the reported parameters. Calculations were checked for agreement with fluence. The techniques of irradiation on enamel and dentin are reported in Table 3 and Table 4, respectively. The distance of irradiation, irradiation time, scanning motion or spot irradiation, area of irradiation and use of cooling were recorded. The effects on surface morphology change and chemical change on surface properties (carbonate content, microhardness, mineral loss, lesion depth resulting in resistance to demineralization and the synergistic effect with fluoride) were reported.

Results

1. Laser parameters on enamel studies

Seventeen studies examined prevention on enamel caries. The laser parameters and the irradiation technique of these 17 studies are summarized in Table 1 and Table 3, respectively. Frequency was the only parameter reported in all 17 studies. The parameters of three studies had fluence incorrectly reported [7,9,25] and two studies could not be determined [22,34]. Eight out of 10 scanning speeds were not reported.

Power and Pulse energy

The output power range was 0.1W to 2,800W. The wide range in power is related to the mode of operations in the continuous wave and pulse modes. Two continuous wave studies reported 0.115W to 2W delivering 155 mJ to 2000 mJ of pulse energy. Ten studies with a pulse between 1 ms and 50 ms, with 0.1W to 50W delivered 0.001 mJ to 250 mJ pulse energy. Four studies used short pulse (5 μs and 100 μs). Seino et al used 5 μs pulse with ~~a~~ power of 0.5W delivered calculated pulse energy of 0.0025 mJ [25]. Power in the other three studies were calculated to be 2,400W and 2,800W, and delivered 14 mJ and 240 mJ pulse energy. Unlike the wide output power range in these enamel studies, the average power range was between 0.05W and 3.2W.

Spot area and fluence

Beam diameter or spot size (diameter of the spot) determines the spot area of irradiation. The area of the spot is calculated by the formula: $\pi D^2/4$ cm^2, where D is the diameter of the spot size. The spot size was reported in all but two studies [21,22]. One of these two studies only reported spot area [21]. There was a typo error in reporting the spot size unit as area (mm^2) [15,16]. Fluence is pulse energy divided by spot area. Miscalculating the spot area would lead to an error in fluence reported. Of the 17 studies, fluence was reported in 11 studies. In nine out of 11 the studies, the reported fluence was in agreement with the other parameters [8,11-14,16,20,24,26]. The reported fluence in two studies was lower than the re-calculated fluence [7,9]. Of the six studies without reported fluence, the fluence could not be calculated in two studies [22,34]. Studies using continuous wave delivered fluence from 16.5 to 27.7 Jcm^{-2}. Studies with pulse at 1 ms to 50 ms delivered fluence between 1.5 and 16 Jcm^{-2}, whereas shorter pulse studies (5μs and 100μs) delivered fluence from 0.3 to 28.6 Jcm^{-2}.

Irradiation distance and technique

Spot irradiation distance in the studies varied between less than 1 mm [14] and 370 mm [21]. Ten studies employed scanning motion and seven studies employed fixed spot irradiation. The scanning motion speed was not reported in 8 out of the 10 studies on enamel. Two studies reported scanning speed of 1 mms^{-1} [7,8]. Two studies reported no cooling during irradiation [7, 24] and there were no mentions of cooling in the other studies.

2. Laser parameters on dentin studies

Six studies examined prevention on dentin caries. The laser parameters and the irradiation technique of the six studies are summarized in Table 2 and Table 4, respectively.

Power and Pulse energy

Four studies' output power ranged from 0.17W to 480W. They had a pulse range from 10 to 100 ms with power at 0.17W to 54W to deliver a pulse energy from 1.7 to 540 mJ. One study used a short pulse at 5 μs with a calculated output power of 480W to deliver 2.4 mJ pulse energy. The power/energy meter was used in all but one study in which the power could not be determined [28]. The frequency reported range from 1 to 250 Hz with average power ranging from 0.009W to 5.4W.

Spot area and fluence

Five studies used a spot size of 0.3 mm to 2.5 mm with fluence ranging from 2.5 to 11 Jcm^{-2}. One study used a spot size of 0.3 mm reported a high fluence from 280 to 715 Jcm^{-2} [28].

Irradiation distance and technique

The irradiation distance ranged from 5 mm to 198 mm. Three studies used spot irradiation and three studies used scanning motion with a speed ranging from 1 mms^{-1} to 7.5 mms^{-1} [27,29,30]. One study reported no cooling on the sample during irradiation [24], while the other studies did not mention cooling.

Among the 23 studies on enamel and dentin, two studies' parameters could not be determined and another three studies were incorrect. Seven studies did not report the scanning speed.

Discussion

The review of these 23 studies found a caries prevention effect of the 10,600nm CO_2 laser on enamel and dentin [32]. The laser increased the resistance of enamel and dentin against demineralization upon the acid challenge. In addition, the studies reported a synergistic caries prevention effect of laser and fluoride on dentin.

From the Tables provided in this review, there are wide variations in laser parameters and irradiation techniques. Among the 23 studies on enamel and dentin, two studies' parameters could not be determined and another three studies were incorrect. Seven studies did not report the scanning speed. Four studies that listed laser parameters and techniques in a Table format were easily transferred to the tables included here [9,11,24,30]. The influences of these multifactorial variations when comparing laser parameters and techniques among the studies was difficult. In this review, comparisons on individual parameters or techniques were made.

Output power

The studies used different notations in their techniques and parameters. Power, average power output, input power and peak power were used and were interpreted in the "output power" category [8,14,15,23,27]. Mirhashemi [23] reported 0.4W "power," which would produce a fluence of 0.05 Jcm^{-2}. This fluence was unlikely to generate morphological changes of the enamel. If 0.4W was taken as the average power, the fluence would be 5 Jcm^{-2} and this fluence could generate morphological changes of the enamel.

The term "average power output" is confusing because we interpreted it as the average of the "power output" and not as the "average power" of the output. To correlate with the fluence reported, the average power output was taken as the average power in Vieira's study [7]. In other studies, calculations were correct when the average output power was interpreted as the output power [8,27]. We suggest to use the term "mean power output" to avoid the confusion. Pulse duration in microseconds is associated with high output power in an excess of 2,000W [11,13,24]. Seino reported an "output power of 0.5 W" at pulse of 5μs, which would likely to be a notation error [25]. An average power of 0.5 W would give an expected high output power of 2,000 W with a pulse energy of 10 mJ, which would be comparable with other studies.

Calculation of spot area and fluence

Spot size was reported as diameter in millimetre scale. πr^2 (r -radius) is the common formula for calculating spot area. Mistaking diameter as radius in a calculation would reduce the fluence by a factor of four. The fluence calculated as 10 Jcm^{-2} and 28.6 Jcm^{-2} could not correlate with the reported fluence at 5 Jcm^{-2} and 6.6 Jcm^{-2} in Vieira and Correa-Afonso, respectively [7,9]. The lowered fluence reported would likely be due to mistakenly calculating diameter as radius. Seino's [25] error in power notation mentioned earlier not only showed a low power output by microsecond pulse, but also a spot size of 1.25×10^{-4} mm calculated in Table 1 was too small compared with 1.6mm and 2.5mm in other microsecond pulse studies [11,13,24]. The suggested average power of 0.5W would give a spot size of 0.2mm.

Parameters and fluence calculation

In general, studies reported fluence as the main laser parameter in their conclusion [7,8,11,12,21,28,30]. Fluence is defined as pulse energy per square centimetre. The pulse energy can be determined by the laser panel pre-set or measured by energy meter. Pulse energy can also be calculated by measured output power or panel pre-set power with a known pulse duration. Hsu [20] and Klein [16] reported power measured by the power meter being different from the power setting on the laser panel. The measured power was 18% and 80% of the power pre-set. Correctly recording power is important because it is used to determine the fluence and thus affects the study's conclusion. Souza-Gabriel et al. [15] referenced the same parameters in their study as those by Klein et al. [16], but they did not report the measured power resulting in differently calculated fluence from that reported by Klein. Esteves et al. [11] studied the calculated fluence reported by Hsu et al. [14,20] and found it was incorrect. In this review, we found that the calculated fluence of 0.3 Jcm^{-2} in both papers were correct as the power measured was the peak power and not the average power as described by Esteves et al. In this review, 15 out of 23 studies (65%) reported using laser power/energy meter to validate the power. The fluence would be more reliably referenced. Although the other eight studies did not report on using the power measurement, whether the power pre-set would be the same as the actual measured power was unknown.

Fluence and SEM observations

Fowler and Kuroda described chemical and morphological changes of enamel at different temperatures [35]. Irradiation with the laser reduced the carbonate content and hence reduced the enamel's solubility [22]. Loss in carbonate content begin at 100°C. At around 800°C, the maximum loss rate commenced and complete carbonate elimination occurred at 1,100°C [6]. Melting and fusion on enamel and dentin surface would occur if the irradiation technique and parameters employed caused an increased temperature of 1,100ºC. Kantorowitz et al. reported no enamel surface morphology changes by fixed spot irradiation with 12 Jcm^{-2} at 100 μs [13]. However, Steiner-Oliveira et al. [8] reported cracking, melting and fusion with fluence between 6 and 11.5 Jcm^{-2} at 10 ms (the pulse was 100 times longer than that used by Kantorowitz) under motion. In the same study [8], lower fluence at 1 and 3 Jcm^{-2} showed no change in surface morphology. Using Steiner-Oliveira et al.'s [8] same irradiation technique and laser parameters at 10 Jcm^{-2} fluence, Vieira reported similar observations of melting and fusion under the corrected calculated fluence of 10 Jcm^{-2} [7].

Nammour et al. [28] reported the CO_2 laser could be used to prevent dentin caries. However, there was no report on power and pulse durations. Their study is difficult to compare with subsequent studies. In addition, the fluence (280 to 715 Jcm^{-2}) delivered was significantly higher than those employed (0.05 to 11 Jcm^{-2}) in other studies [24,27,29-31].

Spot irradiation and scanning motion speed

The irradiating distances of two laboratory studies at 37cm (for enamel) and 19.8cm (for dentin) would be difficult to transfer into clinical practice [21,24]. An irradiating distance between 1mm and 5mm would be more practical. In addition, a long irradiation time of 9 s to 15 s was reported [11,24]. To hold the irradiating distance for the time required may pose another hurdle in clinical application.

The irradiation time in spot irradiation will directly cause a surface temperature increase, which in turn creates changes in surface morphology. The scanning motion speed can also cause the surface temperature to increase. De Melo et al. [29] and De Souza et al. [27] used the same laser parameters with using the power meter on dentin, delivering fluence of 5 Jcm^{-2} and 6 Jcm^{-2}. De Melo et al. used a motion speed (2mm s^{-1}) that was twice the speed De Souza et al. (1 mms^{-1}) used. This motion showed difference in morphological changes under SEM observation. De Melo et al. [29] showed a whitish appearance, but no carbonization. De Souza et al. [27] showed cracking, fusion and resolidification. The irradiation dose was doubled due to reducing the speed by half. The total dose was further doubled as the sample was irradiated again. Regardless of surface change, both studies showed resistance in demineralization, meaning dentin surface melting was not required to prevent caries progression. At 7.5 mms^{-1} speed, Steiner-Oliveira et al. reported fluence at 11 Jcm^{-2} delivered by the same pulse duration, over 10 times the output power and one-fifth of the frequency [30]. By increasing the motion speed, higher fluence could be employed without visible surface carbonization [30].

Cooling

Water is one of the main chromophores of the CO_2 laser. Thus, water cooling plays a key role in controlling temperature and preventing surface changes of dental hard tissues. Nevertheless, only two studies reported that no cooling device was used [7,24] and no other studies mentioned cooling in the irradiation technique.

Coluzzi et al.'s systematic review on lasers in periodontal therapy found similar shortfalls in laser parameter reports, such as confusing notations, incomplete laser parameter descriptions (70%) and one in 20 clinical studies reported using the power meter [35]. In this review, Mirhashemi acknowledged that reproducing enamel morphological features relies not only on the same laser parameters, but also the irradiation technique [23]. The limitations in this review resulted in the parameters on enamel and dentin not being compared. The laser parameters and techniques were collected to the best of the authors' interpretation, as it was difficult to clarify data from the correspondence authors. This review was not intended to scrutinise the accuracy of the studies.

From this review, five steps are suggested when reporting laser parameters. Firstly, it is advisable to report the laser devise and wavelength, model of manufacturer and geographic location. Secondly, using mean power output instead of average power output would avoid misinterpretation. The output power or energy to be measured should be reported to validate with the machine panel pre-set. The meter's model and manufacturer should also be reported for reference. Thirdly, reporting should include laser panel pre-sets such as power, energy, pulse duration, frequency and average power. Not all the above will be presented in panel pre-set, as there are variations in different laser machines. Fourthly, correct spot area calculations from the spot size or fiber diameter are needed. There are guidelines in reporting parameters for manuscript submission such as *Photobiomodulation, Photomedicine, and Laser Surgery*. Finally, a table to summarize the above parameters and validating the calculated fluence and total dose of irradiation should be included. As for irradiation technique, type of handpiece and fiber, the distance and angle of irradiation, spot irradiation in number of pulses and time of irradiation should be recorded. Irradiation in motion should include the speed, pattern of motion and number of repeated irradiations. The method of cooling or no cooling should also be reported. A table to summarize the above irradiation technique would be useful for reproducing the study.

Conclusion

This review found considerable variations in the included articles' parameters and irradiation techniques reported for the 10,600 nm carbon dioxide laser for caries prevention. The use of power or energy meter to validate the pre-set machine setting is important. Some studies did not provide adequate information on the parameters and the irradiation technique. A few studies reported incorrected parameters or impractical irradiation distance for clinical practice. It is important for researchers to record and provide accurate and complete parameters and techniques in their manuscripts for reference and furthering research projects. Although fluence is the most referenced parameter in research conclusions, irradiation techniques are important for producing the outcome effect.

Table 1. Parameters of the 10,600nm CO_2 laser chosen by studies on prevention of enamel caries

Study: Authors, year [Reference]	Output power / W [OP]	Pulse duration / µs [PD]	Pulse energy / mJ [PE]=OP.PD	Frequency / Hz [F]	Average power / W [AP]=OP.PD.F	Spot size / mm [D]	Spot area / cm² [SA]=πD²÷4	Fluence / Jcm^{-2} [FL]=PE÷SA
Vieira et al. 2015 [7]	[0.7]	10000	7	50	0.35	0.3	(0.0007)	*5*
Steiner-Oliveira et al. 2006 [8]	[0.1–0.8]	10000	(1 - 8)	50	(0.05–0.4)	0.3	(0.0007)	1.5–11.5
Correa-Afonso et al. 2012 [9]	(2)	10000	20	20	0.4	0.3	(0.0007)	*6.6*
Esteves-Oliveira et al. 2009 [11]	(2800)	5	[14]	226	3.2	2.5	(0.05)	0.3
Featherstone et al. 1998 [12]	(5–50)	5000	25–250	10	(0.25–2.5)	1.6	(0.02)	1–12.5
Kantorowitz et al. 1998 [13]	(2400)	100	[240]	10	(2.4)	1.6	(0.02)	12
Hsu et al. 2000 [14]	[0.346]	5000	(1.73)	20	(0.0346)	0.8	(0.005)	0.3
Souza-Gabriel et al. 2010 [15]	2	50000	(100)	2	(0.2)	0.6*	0.008	(12.5)
Klein et al. 2005 [16]	[0.8, 1.6]	50000	(40, 80)	2	(0.08, 0.16)	0.8	0.008	8, 16
Hsu et al. 2001 [20]	[0.346]	5000	(1.7)	20	(0.0346)	0.8	(0.005)	(0.3)
Hsu et al. 1998 [21]	[0.155–0.2]	CW	(155–260)	CW	0.2	(0.55)	0.0094	(16.5–27.7)
Tepper et al. 2004 [22]	2	CW	(2000)	CW	(2)	NA	NA	NA
Mirhashemi et al. 2016 [23]	0.4	1000	(0.4)	10	(0.004)	1	(0.008)	(0.005)
Esteves-Oliveira et al. 2017 [24]	(2800)	5	[14]	226	3.2	(2.5)	(0.05)	0.3
Seino et al. 2015 [25]	0.5	5	(0.0025)	50	(1.25×10^{-4})	(3.32×10^{-3})	(8.7×10^{-8})	28.6
Tagliaferro et al. 2007 [26]	[0.5]	50000	(25)	1	(0.025)	0.8*	(0.005)	5
Mahmoudzadeh et al. 2017 [34]	0.4	NA	NA	5	NA	0.2	(0.0003)	NA

[ ] – value measured by power meter/energy meter; ( ) value calculated; * Fiber diameter; CW – Continuous wave; NA – not available

Italics – cannot correlate

Table 2. Parameters of the 10,600nm CO2 laser chosen by studies on prevention of dentin caries

Study: Authors, year [Reference]	Output power / W [OP]	Pulse duration / µs [PD]	Pulse energy / mJ [PE]=OP.PD	Frequency / Hz [F]	Average power / W [AP]=OP.PD.F	Spot size / mm [D]	Spot area / cm² [SA]=$\pi D^2 \div 4$	Fluence / Jcm^{-2} [FL]=PE÷SA
Esteves-Oliveira et al. 2017 [24]	(480)	5	[2.4]	250	0.61	2.5	(0.05)	0.05
De Souza-Zaroni et al. 2010 [27]	[0.17–0.42]	10000	(1.7–4.2)	50	(0.09–0.21)	0.3	(0.0007)	2.5–6
Nammour et al. 1992 [28]	NA	NA	(200–500)	5	(1–2.5)	0.3	(0.0007)	280–715
De Melo et al. 2014 [29]	[0.37, 0.42]	10000	(3.7, 4.2)	50	(0.185, 0.21)	0.3	(0.0007)	5 , 6
Esteves-Oliveira et al. 2011 [30]	(38, 54)	10000	[383, 540]	10	3.8, 5.4	2.5	(0.05)	8 , 11
Gao et al. 2006 [31]	0.09	100000	[8.9]	1	(0.009)	1	(0.008)	1.14

[ ] – value measured by power meter/energy meter; ( ) value calculated; * Fiber diameter; CW - Continuous wave; NA – not available

Table 3. Studies of irradiation techniques and effects of the CO_2 (10,600nm) lasers on enamel

Study: Authors, year [Reference]	Distance (mm)	Spot/ Motion	Irradiation time / Area	Water cooling	Surface morphology change	Chemical change and effects
Vieira et al. 2015 [7]	10	Motion (1mm/s)	30s × 1–4 times/4mm^2	No	Melting and fusion	Reduced carbonate content, Increased microhardness, Resistant to demineralisation
Steiner-Oliveira et al. 2006 [8]	10	Motion (1mm/s)	10s over fissure / NA	NA	No change at 3 J/cm^2, melting at 6 J/cm^2	Reduced carbonate content, Reduced mineral loss, Resistant to demineralisation
Correa-Afonso et al. 2012 [9]	2.5	Motion	30s / 14mm^2	NA	Cracks	Increased microhardness, Resistant to demineralisation
Esteves-Oliveira et al. 2009 [11]	198	Spot	9s, 2036 pulses / NA	NA	No change	Reduced lesion depth, Resistant to demineralisation
Featherstone et al. 1998 [12]	NA	Spot	2.5s 25 pulses	NA	NA	Reduced mineral loss, Resistant to demineralisation
Kantorowitz et al. 1998 [13]	NA	Spot	1–100 pulses	NA	Little or no change	Increased resistant to demineralisation
Hsu et al. 2000 [14]	<1	Spot	1s × 4 times / 4mm^2	NA	No change	Reduced mineral loss, Reduced lesion depth
Souza-Gabriel et al. 2010 [15]	5	Motion	2 times 2 mm^2	NA	Regular and melted surface	Resistant to demineralisation
Klein et al. 2005 [16]	5	Motion	30s × 2 times / 2.3mm^2	NA	Melting and fusion	Reduced mineral loss, Resistant to demineralisation
Hsu et al. 2001 [20]	<1	Spot	1s × 4 times / 4mm^2	NA	No change	Increased microhardness, Reduced mineral loss, Resistant to demineralisation
Hsu et al. 1998 [21]	370	Spot	2–8s / NA	NA	NA	Reduction in enamel solubility, Increased mineral density
Tepper et al. 2004 [22]	4	Motion	15s / NA	NA	Mosaic cracks, spots of melting	Reduction of enamel solubility
Mirhashemi et al. 2016 [23]	NA	Motion	10s × 2 times / NA	NA	Burned, micro-fractures	Laser and control samples had no significant difference
Esteves-Oliveira et al. 2017 [24]	198	Spot	9s / NA	No	NA	Reduced mineral loss, Resistant to demineralization
Seino et al. 2015 [25]	10	Motion	45s / 25mm^2	NA	No change	Less mineral loss, Resistant to demineralisation
Tagliaferro et al. 2007 [26]	5	Motion	30s / 4mm^2	NA	NA	No change in mineral loss, Resistant to demineralisation
Mahmoudzadeh et al. 2017 [34]	5	Motion	20s / 24mm^2	NA	Melting, cracks and craters	Increased microhardness, Resistant to demineralisation

NA – not available

Table 4. Studies of irradiation techniques and effects of the CO_2 (10,600nm) lasers on dentin

Study: Authors, year [Reference]	Distance (mm)	Spot/ Motion	Irradiation time / Area	Water cooling	Surface morphology change	Chemical change and effects
Esteves-Oliveira et al. 2017 [24]	198	Spot	15s, 2745 pulses / NA	No	NA	Increase microhardness, Reduced mineral loss, Resistant to demineralisation
De Souza-Zaroni et al. 2010 [27]	5	Motion (1mm/s)	5s, × 2 times / 4mm^2	NA	Cracking, fusion, and resolidification	Reduced mineral loss, Resistant to demineralisation
Nammour et al. 1992 [28]	NA	Spot	4s, 20 pulses / NA	NA	Cracking at 565 J/cm^2	Resistant to demineralisation
De Melo et al. 2014 [29]	10	Motion (2mm/s)	10s / 2.3mm^2	NA	Whitish appearance, but no carbonisation	Increase microhardness, Reduced mineral loss, Resistant to demineralisation
Esteves-Oliveira et al. 2011 [30]	100	Motion (7.5mm/s)	3 pulses × 2 times / NA	NA	No carbonisation	Reduced loss of calcium ions
Gao et al. 2006 [31]	NA	Spot	0.1s, × 4 times / NA	NA	NA	Increased fluoride uptake Reduced lesion depth

NA – not available

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