Hypersensitive Teeth: Conventional vs Laser Treatment.
Part II: Laser Treatment of Dentin Hypersensitivity

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ABSTRACT: Dentin hypersensitivity is a painful response to a non-noxious stimulus applied to exposed dentin. Two processes may expose dentin: loss of enamel and/or loss of cementum. Loss of enamel occurs by attrition associated with occlusal function, by abrasion from dietary components or incorrect toothbrushing, or by erosion associated with environmental or dietary components, particularly acids. Exposure of root dentin is also multifactorial. Periodontal disease with gingival recession, some forms of periodontal surgery, and overzealous brushing are important etiological factors that expose root dentin. In addition, in some individuals the cementum and enamel do not meet, exposing an area of dentin.

The management of this condition requires a good understanding of the complexity of the problem as well as the variety of treatments available. Some authors report that lasers may provide reliable and reproducible treatment of dentin hypersensitivity. One concern for laser safety is that the heat produced at the irradiated root surface may diffuse to the pulp, causing irreversible pulpal damage. The protocols advocated today for laser-assisted treatment of hypersensitivity appear to be safe and effective.

Keywords: dentin hypersensitivity, laser treatment, low-output lasers, middle-output lasers, pulpal damage, treatment effectiveness.

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Dentin hypersensitivity may be defined as pain arising from exposed dentin, typically in response to chemical, thermal, tactile, or osmotic stimuli, which cannot be explained as arising from any other form of dental defect or pathology.[1-4] Dentin hypersensitivity seems to be a common problem, with various reports indicating an incidence between 8% and 57% of the population.[5-7] According to Bartold,[8] the most commonly affected teeth are the maxillary premolars, and the most frequent initiating factor is cold drinks.

Treatments for dentin hypersensitivity are numerous,[9-16] but to date, no single agent or form of treatment has been found effective for all patients. Grossman[17] suggested that the ideal desensitizer should be (1) not unduly irritating to the pulp, (2) painless when applied, (3) easy to apply, (4) consistently effective, (5) permanently effective, (6) quick acting, and (7) should not cause tooth discoloration. Some authors report that lasers can provide reliable and reproducible treatment of this condition. Since the ruby laser was developed by Maiman,[18] researchers have investigated laser applications in dentistry.

LASER TREATMENT OF DENTIN HYPERSENSITIVITY

With the advent of laser technology and its growing utilization in dentistry, an additional therapeutic option is available for the treatment of dentinal pain.[19,20] The laser is a device which transforms light of various frequencies into chromatic radiation in the visible, infrared, or ultraviolet ranges with all the waves in phase, capable of mobilizing immense heat and power when focused at close range.[21,22] The word "LASER" is an acronym derived from Light Amplification by the Stimulated Emission of Radiation. The laser, interacting with the tissue, can cause different tissue reactions according to its wavelength, power, and the optical properties of the tissue. The wavelength is arguably the most important determinant in how light affects the tissue.[23] Wavelength is defined as the distance between adjacent peaks of an electromagnetic or light wave.

In reality, lasers are not new in dentistry. Some of the first reports of their use date to the late 1960s. Stern and Sognnaes[24] were the first to investigate the effects of the ruby laser on the dental hard tissues. They reported that craters in enamel could be produced under the parameters used, and much larger craters in dentin. Gordon[25] recorded a bright plume ejected from the impact area, which consisted of vaporized dental tissue. It was concluded that care must be taken to protect adjacent or even distant tissues. Other investigations[26] on the use of the ruby laser in extracted teeth revealed a degree of destruction in the cavities in the dentin formed by the laser probe. Melting drops and spheres were apparent, which sometimes had the appearance of burst shells.

Heat generated by tissue absorption of laser energy, not the light itself, vaporizes the tissue. One of the factors that influence the effect of this thermal energy is the type of tissue that is irradiated.[23] Teeth are markedly heterogeneous structures, and the thermal properties of the components in each tissue differ. Enamel has a higher thermal conductivity than dentin, with a mean value of 2.23×10^{-3} cal/s/cm^2/°C/cm. It seems that tubule direction does not influence the thermal conductivity of dentin. However, an actual variation exists from one tooth to another, and variations are possible in sample preparation.[27] Braden[28] found good conformity between the experiment and the mathematical theory of heat conduction. Since the temperature changes in dental tissues are rather transient, the thermal diffusity (thermal conductivity/specific heat x density) is more relevant in establishing the protection of the dental tissues from a thermal shock.[29] Later studies of the density and specific heat of teeth indicated that transient heat conduction occurs more readily in enamel than in dentin, and a difference of over 250% in the diffusity of dentin and enamel was found. It was apparent that in teeth subjected to a sudden change in temperature, the enamel tends to reach the new temperature much more rapidly than the dentin,[30] and the reaction temperatures are inversely proportional to the enamel density.[31]

Laser studies intend to find the correct parameters to produce the desirable result with the least side effects. Today, two general classes of laser exist for medical and dental applications. The low output or "soft" lasers, which are a source of cold (athermic) low energy thought to stimulate cellular activity, and the middle output or "hard" (thermic) lasers utilized in surgery to cut, coagulate, and vaporize.[32-34]

LOW-OUTPUT LASERS

The use of low-output lasers was primarily recommended for the relief of pain, directly or at an acupuncture point, and in the regeneration of soft and hard tissue.[35] The stimulation of wound healing in rats after irradiation with He-Ne laser is supported by several studies.[36,37] It also seems that low-energy lasers accelerate bone healing.[38,39] The stimulation of dentinogenesis is also possible after low-output laser irradiation, and the formation of a dentin bridge and calcified particles can maintain the vitality of the pulp.[40] An interesting application of low-energy lasers would be in the prevention of periodontal disease, as the dental plaque deposition in hamsters was controlled after He-Ne laser irradiation.[41] Moreover, in recent years, there has been increasing interest in hard tissue applications of low-output lasers.[42] The low-output lasers are chosen for the treatment of mild cervical dentin hypersensitivity. Nevertheless, the middle-output power lasers still show the best results in the treatment of severe cases of dentin hypersensitivity.[43]

He-Ne Laser

Table 1 shows the laser parameters used for the He-Ne laser (632.8 nm), and their treatment effectiveness. Gelskey et al[44] reported that He-Ne lasing reduced dentin hypersensitivity to air by 63% and to mechanical stimulation by 61% over a 3-month period. The combined use of He-Ne and Nd:YAG laser treatment gave similar results.

Table 1 Laser parameters and treatment effectiveness of He-Ne laser (wavelength 632.8 nm)

Investigators	Irradiation parameters	Effectiveness
Senda et al (1985) in vivo study §	6 mW, 5 Hz or cw for 2-3 min	84%
Matsumoto et al (1986) in vivo study §	6 mW, 5 Hz for 1-3 min	90%
Gomi et al (1986) in vivo study §	6 mW, 5 Hz, for 3 min	100%
Kanamura et al (1986) in vivo study §	6 mW, 5 Hz, for 3 min	90%
Wilder-Smith (1988)[45] in vivo study	6mW, 5 Hz, 2.5 min	No advantage over conventional treatment
Matsumoto et al(1988), in vivo study §	6 mW, cw for 0.5-3 min	90%
Mezawa et al (1992) in vivo study §	6 mW, cw for 5 min	55%
Gelskey et al (1993),[44] (He:Ne laser alone and He:Ne + Nd:YAG laser), in vivo study	(He:Ne + Nd:YAG), 30-100 mJ/p at 10 pps	Effective by 63% to air stimulus and by 61% to mechanical stimulus when He:Ne laser was used alone
Orchardson and Whitters (2000),[46] in vivo study	He-Ne laser alone /He-Ne + Nd:YAG (0.3 W, 30-150 mJ/p, 10-30 pps)	Little or no effect on ferret in tradental nerve excitability

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A study conducted by Wilder-Smith,[45] on the other hand, has shown no advantage of the use of He-Ne laser over the conventional methods in treating this condition. The results of the study by Orchardson and Whitters[46] support this conclusion. They found that irradiation with a He-Ne laser alone or with the Nd:YAG laser at 0.3 W power produced no discernible effects on intradental nerve response when dentin was mechanically stimulated.

GaAlAs Laser

The wavelengths of GaAlAs lasers that are used for the treatment of dentin hypersensitivity are between 660 and 900 nm. Table 2 shows the laser parameters used for the GaAlAs laser at 660 nm and their treatment effectiveness. In a clinical evaluation of GaAlAs laser therapy and fluoride varnish, both treatments were found to be effective, with the GaAlAs laser showing better results in the treatment of severe cases of dentin hypersensitivity.[47] When the effectiveness of two types of GaAlAs lasers with 660 nm wavelength (red spectrum) and 830 nm wavelength (infrared spectrum) was compared, greater therapeutic effects were observed with the 660-nm laser.[48] Additionally, a study evaluated the effectiveness of the maximum (5 J/cm^2) and minimum (3 J/cm^2) energies of the GaAlAs laser 670-nm wavelength in alleviating dentin hypersensitivity. The treatment was effective immediately and after a follow-up of 60 days, with no significant difference between the maximum and minimum applied energies (Table 3).[49]

Alleviation of symptoms of dentin hypersensitivity was obvious after GaAlAs laser treatment with a wavelength of 830 nm, and there were no adverse reactions reported.[50] The combined use of the GaAlAs laser with fluoridation enhances the treatment effectiveness by more than 20% over that of laser treatment alone.[51] In another study, the desensitizing efficacy of the GaAlAs laser and the dentin bonding agent Scotchbond (3M; St Paul, MN, USA) were evaluated. It was concluded that the dentin bonding agent performed better in treating dentin hypersensitivity. However,

Table 2 Laser parameters and treatment effectiveness of GaAlAs laser (wavelength 660 nm)

Investigators	Irradiation parametes	Effectiveness
Corona et al (2003),[47] in vivo study	15 mW, cw for 10 s	Both fluoride varnish and GaAlas laser were effective.
Ladalardo et al (2004),[48] in vivo study	35 mW, cw for 114 s	The 660nm GaAlAs laser was more effective than the 830 nm.

Table 3 Laser parameters and treatment effectiveness of GaAlAs laser (wavelength 670 nm)

Investigators	Irradiation parameters	Effectiveness
Marsilio et al (2003),[49] in vivo study	15 mW, 3 J/cm^2 for 1 min and 54 sec (maximum 6 times)	86.53% effectiveness when 3 J/cm^2 energy was applied
	15 mW, 5 J/cm^2 for 3 min and 10 s (maximum 6 times)	88.88% effectiveness when 5 J/cm^2 energy was applied

Table 4 Laser parameters and treatment effectiveness of GaAlAs laser (wavelength 780 nm)

Investigators	Irradiation parameters	Effectiveness
Matsumoto et al (1985), in vivo study §	30 mW, cw for 0.5 -2.5 min	100%
Matsumoto et al (1985), in vivo study §	30 mW, cw for 0.5 -3 min	85%
Ebihara et al (1988), in vivo study §	30 mW, cw for 1 -2 min	58.5%
Furuoka et al (1988), in vivo study §	30 mW, cw for 0.5 -3 min	92%
Kawakami et al (1989), in vivo study §	30 mW, cw for 0.5 -3 min	95%
Sato et al (1989), in vivo study §	30 mW, cw for 0.5 -3 min	88.8%
Hoji (1990), in vivo study §	30 mW, cw for 0.5 -3 min	83.6%

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both were considered effective over an evaluation period of 30 days.[52]

The mechanism by which low-output lasers exert their effect appears to be the stimulation of the Na+/K+ pump in cell membranes. Stimulation of the pump hyperpolarizes the membrane, thus increasing the nerve-firing and pain threshold.[50] It is also likely that the low-output lasers block the depolarization of

Table 5 Laser parameters and treatment effectiveness of GaAlAs laser (wavelength 790 nm)

Investigators	Irradiation parameters	Effectiveness
Yamaguchi et al (1990), in vivo study §	30 mW, cw for 1 min	60%
Kumazaki et al (1989), in vivo study §	30 mW, cw for 3 min	69.2%
Tengrungsun and Sangkla (2008),[52] in vivo study	30 mW, cw for 1 min	Effective but rate unknown. When compared with the dentin bonding agent (Scotch-bond), the bonding agent performed better.

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Table 6 Laser parameters and treatment effectiveness of GaAlAs laser (wavelength 830 nm)

Investigators	Irradiation parameters	Effectiveness
Matsumoto et al (1990), in vivo study §	60 mW, cw for 0.5-3 min	100%
Setoguchi et al (1990), in vivo study §	30 mW, cw for 1 min	85%
Hamachi et al (1992), in vivo study §	40 mW, cw for 0.5-3 min	83.9%
Wakabayashi et al (1992a), in vivo study §	40 mW, cw for 0.5-3 min	97%
Mezawa et al (1992), in vivo study §	30 mW, cw for 5 min	58%
Tachibana et al (1992), in vivo study §	40 mW, cw for 0.5-3 min	92.5%
Tachibana et al (1992), in vivo study §	20 mW, cw for 0.5-3 min	30%
Gerschman et al (1994),[50] in vivo study	30 mW, cw for 1 min	65% for tactile sensitivity, 67%, for thermal sensitivity
Liu and Lan (1994),[51] in vivo study	40-100 mW, cw for 15-60 sec	70-88%
Ladalardo et al (2004),[48] in vivo study	35 mW, cw for 114 sec	Effective but the rate is unknown.

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C-fiber afferents in the dental pulp,[41] but they do not suppress Aδ-fiber afferents.[53]

Excimer Lasers

Stabholz et al[54-56] studied the effects of excimer lasers on human dentinal tubules (Table 8). It was demon-

Table 7 Laser parameters and treatment effectiveness of GaAlAs laser (wavelength 900 nm)

Investigators	Irradiation parameters	Effectiveness
Iida et al (1993), in vivo study §	2.4 mW, 1.2 kHz for 2.5 min	73.3-100%

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Table 8 Laser parameters and treatment effectiveness of Excimer lasers (XeCl, wavelength 308 nm; ArF, wavelength 193 nm)

Investigators	Irradiation parameters	Effectiveness
Stabholz et al (1993),[54] in vitro study	XeCl, 0.5 J/cm^2-7 J/cm^2, 25 Hz, 4 s	At fluences of up to 1 J/cm^2: melted dentin which closed the dentinal tubules.
Stabholz et al (1995),[55] in vitro study	XeCl, 0.7 J/cm^2, 25 Hz, 4 s	Decreased dentin permeability
Stabholz et al (1993),[56] in vitro study	ArF, 0.2-15 J/cm^2, 25 Hz, 5 s	At fluences ≥ 5 J/cm^2: sealing of the dentinal tubules. At 15 J/cm^2: melted dentin with large cracks.

strated that the application of a XeCl excimer laser at fluences not exceeding 1 J/cm^2 caused melting of dentin and closure of dentinal tubules.[54] In a later study under similar conditions, the dentinal tubules of irradiated dentin showed less dye penetration than the nonlased dentin.[55] Laser-treated areas also appeared smoother, and the dentinal smear layer was melted and resolidified after the use of the ArF-193 nm at a fluence of 5 J/cm^2.[56]

MIDDLE-OUTPUT LASERS

Erbium lasers

The energy of the Er:YAG laser (2640 nm), being highly absorbed in water and less in hydroxyapatite,[33,34,57,58] appears to be both effective and safe for the treatment of dental hard tissues without significant thermal effects.[59-62] The energy settings used for the treatment of dentin hypersensitivity are lower than the ablation thresholds of dental hard tissues, and it is believed that Er:YAG laser light evaporates the superficial layers of the dentinal fluid, producing a decrease of the rate flow.[63]

Few published studies are available concerning the desensitizing treatment with the Er:YAG laser (Table 9). Schwarz et al[63] compared the effects of the Er:YAG laser (80 mJ/p, 3 Hz) to Dentin Protector desensitizing agent (Vivadent; Schaan, Liechtenstein) in the treatment of hypersensitive dentin. Both treatments were effective in reducing the symptoms of dentin hypersensitivity, and the positive results of the Er:YAG laser were maintained after 6 months. A preliminary study also showed that the Er:YAG laser, when used with energy settings lower than the ablation threshold of dental hard tissues, decreased dentin permeability due to partial occlusion of the dentinal tubules, and consequently decreased dentin hypersensitivity.[64] Other studies also support the tubule-occluding effect of the Er:YAG and the Er,Cr:YSGG lasers and the reduction in dentin permeability.[65,66]

In a comparative evaluation of the effects of Er:YAG and Nd:YAG lasers, both seemed to produce occlusion of the dentinal tubules.[67] According to this study, the Nd:YAG laser at 1 W power was more effective than the Nd:YAG at 0.5 W or Er:YAG at 0.3 W in occluding the tubules. When the performance of the Er:YAG and Nd:YAG lasers was evaluated in vivo, it was demonstrated that both had an acceptable therapeutic result

Table 9 Laser parameters and treatment effectiveness of Er:YAG laser (wavelength 2640 nm)

Investigators	Irradiation parameters	Effectiveness
Schwarz et al (2002),[63] in vivo study	80 mJ/p, 3 Hz for 2 min	Effective and more prolonged positive results when compared with Dentin Protector but rate is unknown.
Birang et al (2007),[68] in vivo study	100 mJ/p, 3 Hz for 60 s, 2 times	Effective but rate is unknown.
Ipci et al (2009),[70] used in vivo study	60 mJ/p, 30 Hz for 10 s	57-59% when Er:YAG laser alone 55-61% when Er:YAG laser used in combination with NaF gel

which was present for at least 6 months, although the Nd:YAG laser proved to be more effective in alleviating symptoms of hypersensitivity.[68]

In the literature, there are few studies of the Er:YAG laser plus fluoride application for the treatment of dentin hypersensitivity. In an in vitro study,[69] the combined use of Er:YAG laser and NaF application to the dentin surface was evaluated, demonstrating that the dentinal tubules were more markedly occluded than when the Er:YAG laser was used alone. However, in a clinical study by Ipci et al,[70] the combination of Er:YAG laser and NaF gel did not show significantly greater effectiveness compared to the Er:YAG laser used alone. Both treatment modalities proved effective in treating hypersensitivity immediately and after a follow-up period of 6 months.[70]

Nd:YAG laser

Renton-Harper and Midda[71] studied the effects of the Nd:YAG laser (1064 nm) for the treatment of cervical hypersensitivite dentin in periodontal patients. The response to cold stimuli was reduced, but long-term efficacy was not demonstrated. When in a randomized, double-blind study, the effectiveness of a He-Ne laser treatment and a He-Ne plus Nd:YAG laser treatment was compared, both were found to be effective to an equal degree for a period of 3 months.[44] Similar results were obtained from the study by Lan and Liu,[72] where a 65% reduction in dentin hypersensitivity was found over a period of 3 months when the teeth were exposed to air, and a 72% reduction when a mechanical stimulus was applied. Table 10 gives an overview of the clinical studies that evaluated the effectiveness of Nd:YAG laser in the treatment of dentin hypersensitivity.

When the effectiveness of the use of three different settings (0.3 W, 0.6 W, 1 W) of the Nd:YAG laser on exposed dentin was examined, no significant difference could be found, and it was proposed that laser irradiation can be effective even at very low settings.[73] The use of black ink as dye enhancement was proposed to improve the effectiveness of the treatment of dental hypersensitivity.[74] Chromophore dyes can be employed to increase the energy absorption, and therefore the therapeutic effect of laser can be achieved at lower settings.[75,76]

In a study by Lier et al,[77] no statistically significant difference was found between laser treated and non-treated areas. It was suggested that a strong placebo effect may be present in trials of dentin hypersensitivity. The effects, however, persisted for 4 months. Long-term effectiveness of up to 6 months was also demonstrated in another study, which pointed out that the reduction of cervical dentinal hypersensitivity was statistically greater when the etiological factors were removed prior to treatment.[78]

In vitro studies were also conducted in order to identify the parameters sufficient to produce visible changes to the dentin surface, which are lower than those used for ablation, with the least side effects to the adjacent tissues. The physical modification threshold of dentin, which is defined as the first interaction that occurs causing an observable change in dentin, was identified after the use of Nd:YAG and Ho:YAG lasers.[79] It was concluded that the family of YAG lasers can produce partial closure of the dentin tubules without thermal side effects on the adjacent tissues. In a similar study, treatment of dentin at threshold illumi-

Table 10 Laser parameters and treatment effectiveness of pulsed Nd:YAG laser (wavelength 1064 nm)

Investigators	Irradiation parameters	Effectiveness
Matsumoto et al (1985), in vivo study §	10 W, for 0.1 s, 5 times	100%
Renton-Harper and Midda (1992),[71] in vivo study	100 mJ/p, 10 Hz for 2 min	100 % effectiveness and at 14-day recall the greatest desensitizing effect
Gelskey et al (1993)[44] (He:Ne + Nd:YAG laser), in vivo study	Nd:YAG: 30-100 mJ/p, 10 Hz, He:Ne	Effective by 58% to air stimulus and by 61% to mechanical stimulus
Lan and Liu (1996),[72] in vivo study	30 mJ, 10 Hz, for 2 min	Effective by 65% to air stimulus and by 72% to mechanical stimulus
Kawada et al (1996), in vivo study §	2 W for 1 s, 20 times	4.8-85.7%
Gutknecht et al (1997),[73] in vivo study	0.3-1 W, 10 Hz for 30-90 s	83-93%
Yonaga et al (1999),[74] in vivo study	2 W, 20 Hz, for 0.5-60 s, black ink	75.5-95.6%
Kobayashi et al (1999), in vivo study §	1.5 W, 15 Hz for 1 min	51.5-95.8%
Lier et al (2002),[77] in vivo study	30 s without a coolant, then 90 s with water as a coolant	No significant difference between test and control group
Ciaramicoli et al (2003),[78] in vivo study	40 mJ, 25 Hz, 1W, 30 s	Effective but statistically greater reduction of hypersensitivity when etiologic factors were removed prior to treatment.
Birang et al (2007),[68] in vivo study	Nd:YAG: 1W, 15 Hz for 60 s, 2 times Er:YAG: 100 mJ/p, 3 Hz for 60 s, 2 times	Both lasers were effective, but rate is unknown. Nd:YAG laser performed better than Er:YAG laser.

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nance with Nd:YAG and Ho:YAG lasers created a recrystallized surface layer that was not, however, totally impermeable due to the presence of cracks and voids.[80] The study by Marin et al[81] indicated that at 0.50 W and 10 Hz with an exposure time of 15 s, a closing of the tubule orifices was obtained without any thermal damage to the pulp. Moreover, the penetration depth of the Nd:YAG laser in dentin varied from 1 to 7 mm, using 30 and 40 mJ energy levels, respectively.[82]

Other investigations intended to measure the dentin permeability and the morphological changes on the dentin surface produced by laser energy. According to the hydrodynamic theory of dentin hypersensitivity, anything which can decrease dentin permeability should result in a decrease in dentin hypersensitivity. White et al[83] determined the hydraulic conductance, which is defined as the permeability of dentin and is a measurement of the fluid flow from the pulp through the dentinal tubules. They found a trend toward decreased hydraulic conductance at the higher power levels of Nd:YAG laser irradiation. However, scanning electron micrographs showed partially occluded dentinal tubules.

Permeability measurements were also carried out in the study by Schaller et al.[84] Analysis of the data showed a significant influence of the Nd:YAG laser treatment on the permeability of dentin, since the tubules were partially occluded, although the presence of craters and inconsistently lased areas questioned the feasibility of the treatment. The sealing depth of Nd:YAG laser on human dentinal tubules at an energy

Table 11 Laser parameters and treatment effectiveness of Nd:YAG laser combined with desensitizing agents

Investigators	Irradiation parameters	Effectiveness
Lan et al (1999),[90] in vitro study	30 mJ, 10 pps, 2 min (+ sodium fluoride varnish)	90% effectiveness (occlusion of the dentinal tubules)
Kumar and Mehta (2005),[91] in vivo and in vitro study	30 mJ, 10 pps, 2 min (+ 5% sodium fluoride varnish)	An impressive efficacy when compared with either treatment alone
Lee et al (2005),[93] in vitro study	30 Hz, 160 mJ/p (G- mode) and 30 Hz, 330 mJ/p (G+mode), (+ bioglass)	Occlusion of the dentinal tubules
Hsu et al (2006),[92] vitro study	33 mJ, 50 pps for 2 min	Occlusion of the dentinal tubules

of 30 mJ/p with 10 pp/s was found to be ~4 µm in the center and 3 µm at the margin of the lased surfaces.[85] The same authors evaluated the morphological changes of hypersensitive dentin after Nd:YAG laser irradiation; the absence of protrusive rods in the dentin surface was interpreted as sealing of the tubules.[86] They also suggested that the irradiation energy of Nd:YAG laser can be used at different parameters to fuse a low-melting-point bioactive glass for repairing root fractures.[87]

Morphological changes of the dentin surface with occluded dentinal tubules were also observed in a study by Naylor et al.[88] When the occluding effect of Nd:YAG laser and Sensodyne toothpaste (active ingredient strontium choride) were compared, both treatments reduced dye penetration through exposed dentinal tubules. However, the occluding effect of Nd:YAG laser occurred immediately, whereas treatment with Sensodyne toothpaste produced positive results after at least 3 weeks.

Some studies tried to evaluate the combined occluding effect of Nd:YAG laser with various desensitizing agents (Table 11). The application of sodium fluoride varnish with Nd:YAG laser occluded > 90% of exposed dentinal tubule orifices[90] and had a greater efficacy when compared with either treatment alone.[91,92] Laser irradiation can also melt a highly biocompatible material, such as bioglass, to achieve a greater sealing effect of the dentinal tubules.[93] Moreover, fluoride application was found to be effective in increasing the resistance of bovine dentin to erosion, whereas laser irradiation alone was unable to increase the dentin's resistance to erosive losses.[94]

Based on the described results, it seems that pulsed Nd:YAG laser irradiation can be effective in treating hypersensitive dentin. Next to the laser-induced occlusion or narrowing of the tubules, a direct nerve analgesia has been suggested as the desensitizing effect. It has been hypothesized that the laser energy interferes with the sodium pump mechanism, changes the cell membrane permeability and/or temporarily alters the endings of the sensory axons.[95] In the case of low-energy Nd:YAG laser irradiation, a transient increase of blood flow was demonstrated that is believed to enhance wound healing and relieve pain.[96]

The reduced intradental nerve responsiveness after lasing of dentin could be due to several factors, such as tubule occlusion, interference with the hydrodynamic mechanism by which stimulus-induced fluid flow in dentinal tubules is converted into nerve activity, or through a direct action on the nerves. Laser-induced depression of intradental nerve excitability was to some extent reversible,[97] and it was concluded that the optimum laser conditions to achieve more effective analgesia have yet to be determined. Recovery was less complete only when irradiation was greater than or equal to 2 W power, and it seems that lasing can produce temporary suppression of intradental nerve responses to mechanical stimulation.[98] Since lasing blocked conduction in both A-and C-fibers in isolated spinal nerves, it appears likely that lasing could diminish all categories of sensations, including pain. A dose-dependent block of action potential conduction in nerve fibers was also demonstrated in the pulp chambers of teeth in vitro and in vivo.[46,99]

On the other hand, Goodis et al,[100] using fetal calf serum to simulate dentinal fluid, found a transient decrease in dentin permeability. They concluded that the dentin surface was not affected by the laser energy, since the reduction in permeability was transitory. They assumed that the laser energy produced coagulation of

Table 12 Laser parameters and treatment effectiveness of KTP laser combined with desensitizing agents (wavelenght 532 nm)

Investigators	Irradiation parameters	Effectiveness
Goharkhay et al (2007),[101] in vitro study	1W for 5 s with 20 s break, 6 times + fluoride compound	Effective but rate is unknown

Table 13 Laser parameters and treatment effectiveness of CO_2 laser (wavelength 10600 nm)

Investigators	Irradiation parameters	Effectiveness
Zhang et al (1998),[116] in vivo and in vitro study	1W, c.w, for 0.5 s with 0.5 s break (total lasing time from 5-10 s), water coolant	100% effective but after 1 week sensitivity had recurred in almost half of the cases.

proteins contained in the fetal calf serum, which occluded the tubules.

Moreover, Lan et al[86] proposed that the mechanism of the Nd:YAG laser's effect on dentin is caused by thermal energy absorption. The thermal energy caused the hydroxyapatite crystals to melt partly or completely, and finally the dentinal tubules were occluded.

KTP laser

The KTP laser, a modified Nd:YAG laser emitting at a wavelength of 532 nm, has been investigated for a variety of surgical applications, but it was not until a few years ago that it was implemented in the field of dentistry.

Goharkay et al[101] investigated the effect of KTP, diode, and CO_2 laser irradiation with and without prior application of fluoride compounds (Table 12). The KTP laser was used with a bleaching handpiece with a diameter of 5.7 mm at an output power of 1W in continuous wave mode. The teeth were lased for 5 s followed by a 20 s break, and the procedure was repeated 6 times. The combined use of KTP laser irradiation and fluoridation resulted in the occlusion of most of the tubules. However, the best results were achieved after the application of the 0.4% stannous fluoride gel followed by CO_2 laser irradiation.

CO_2 Laser

Early studies investigated the morphological changes produced in enamel and dentin after CO_2 laser irradiation.[102] The enamel appeared fused but brittle, and the dentin was completely destroyed. These changes were probably due to the high temperature increase in the lased areas. The high temperature due to CO_2 laser irradiation was confirmed by means of x-ray diffraction studies.[103,104] Beams of pulsed CO_2 laser at different energy densities produced fractures and holes in dentin.[105] Furthermore, the degree of heat resulting from a reflected 10-W CO_2 laser exposure can be a hazard to surrounding tissues at distances up to 7.0 cm from the focal point.[106] Featherstone and Nelson[107] demonstrated that a CO_2 laser used at low-energy densities was able to fuse enamel and dentin with no damage to the pulp or the adjacent tissues. At that time, the clinical applications of CO_2 laser were concerned with the treatment of dental decay and soft tissue surgery.[108]

There are also some studies that measured the effect of CO_2 laser irradiation on dentin permeability. Bonin et al[109] used a solution of noradrenaline to illustrate the effect of exposure of dog canines to the beam of a CO_2 laser. Noradrenaline induces a vasoconstriction of the pulp, which is followed by a drop in the blood pressure. In this experiment, there was no variation in the blood pressure which was interpreted as sealing of the tubules. One year later, Pashley et al[110] used three different energy levels (11, 113, and 566 J/cm^2) to study the effect of the CO_2 laser on dentin permeability. The lowest and intermediate energy levels increased the permeability of dentin due to loss of the superficial smear layer and crater formation. The higher energy level resulted in a halo region where the tubules were opened. However, the dentin within the

Table 14 Laser parameters and treatment effectiveness of CO_2 laser (wavelength 10600 nm) in combination with fluoridation

Investigators	Irradiation parameters	Effectiveness
Moritz et al (1996),[119] in vivo and in vitro study	0.5 W, c.w, for 5 s with 20 s break, 6 times + 0.4% stannous fluoride gel (Gelkam)	94.5-98.6%
Moritz et al (1998),[120] in vivo and in vitro study	0.5 W, c.w, for 5 s with 20 s break, 6 times + 0.4% stannous fluoride gel (Gelkam)	96.5%
Goharkay et al (2007),[101] in vitro study	0.5 W, c.w, for 5 s with 20 s break, 6 times + fluoride compound	Effective but rate is unknown

crater was almost impermeable. Other authors found the effects of CO_2 laser energy on dentin to range from no visible effects to charring and cracking when different parameters were used, and in that study, CO_2 laser irradiation did not result in a less permeable surface.[111] Other studies showed that CO_2 laser was capable of producing a glazed-like surface.[112,113] It seems that the angle of the laser beam in relation to the exposed dentin surface is a deciding factor for how much energy is absorbed by the dentin and consequently for the morphological changes of the dental tissue.[114]

In another study, changes in dentin permeability after low-energy CO_2 laser irradiation were evaluated using an electrical impedance method. This is a quantitative and nondestructive method of measuring dentin permeability. A transient dentinal dessication was observed, which can alleviate the symptoms of dentin hypersensitivity until rehydration occurs.[115] Similarly, in the study by Zhang et al,[116] the CO_2 laser proved effective in the treatment of this condition without causing any thermal damage to the pulp. However, after one week, sensitivity had recurred in almost half of the cases (Table 13).

On the other hand, when extracted teeth were irradiated with a CO_2 laser, the dentinal tubules were not sealed and the effect of laser energy on dentin varied from cratering up to melting. It was concluded that the changes in the hydroxyapatite crystal were responsible for the observed effects and the increase in the permeability.[117]

Slutzky-Goldberg et al[118] studied the effect of 9600-nm CO_2 laser energy on dentin due to the contradictory results of the effectiveness of 10,600-nm CO_2 laser energy in reducing dentin hypersensitivity. They concluded that 9600 nm CO_2 laser energy can be an alternative treatment of dentin hypersensitivity, since it sealed the dentinal tubules and reduced dentin permeability.

The combined laser treatment and fluoridation resulted in a fusion of stannous fluoride with the dentin surface and a success rate of 94.5%, when success was defined as complete freedom from pain over a period of 3 months. Treatment of the control group with fluoridation alone resulted in no marked improvement.[119] In a later study by the same authors (Table 14), a long-term effect of up to 18 months was demonstrated after the combined CO_2 laser treatment and fluoridation on hypersensitive teeth.[120] The evaluation was based on the subjective criteria of freedom from pain, atomic absorption spectroscopy and scanning electron microscopy. In a recent in vitro study, complete closure of the dentinal tubules was demonstrated only after the combination of 0.4% stannous fluoride gel with CO_2 laser. CO_2 laser irradiation alone produced partially melted and fused areas.[101] CO_2 laser irradiation in combination with fluoride treatment has also yielded promising results in caries prevention.[121-123]

LASER TREATMENT OF DENTIN SURFACES NEAR THE PULP

As soon as the use of the laser in dentistry appeared to be possible, histopathological studies on the pulp tissue after exposing the dentin surface to the laser beam were published. The enthusiasm for dental lasers was tempered by concerns that lasing may damage the tooth pulp. It is commonly believed that temperature increases associated with certain dental procedures pose a serious threat to the vitality of the pulp. Therefore, the determination of threshold values is very important, as they indicate the values beyond which heat becomes a major factor of biological damage. Additionally, there is often a discrepancy between clinical and morphological data, and the lack of clinical symptoms does not constitute evidence that the pulp is free of inflammation.[124,125]

According to Zach and Cohen,[126] an increase in intrapulpal temperature below 2.2°C was observed to fall within a safe range of thermal stress in an observation period of 56 to 91 days. A rise in internal temperature of 5.5°C caused pulp necrosis in 15% of the cases. Temperature increases of 11°C and 16°C resulted in pulp necrosis in 60% and 100% of the cases, respectively.

Goodis et al[127] used an improved method to simultaneously measure temperature at the dentino-enamel junction (DEJ) and the pulpodentin junction (PDJ). Surprisingly, an initial drop in temperature was noted with both measurements. They suggested that the heat generated during cavity preparation is dissipated from the flow of the dentinal fluid. Although dentin is a low conductance tissue, the dentinal fluid seems to act as a heat exchanger. In a study Baldissara et al,[128] average increases of 11.2°C did not appear to damage the pulp, since no signs of inflammation and no reparative processes were detected. In contrast to the observations found in the study by Zach and Cohen,[126] the results suggested a low susceptibility of cells to heat, which does not appear to be a major factor in injury, at least during the study period of 68 to 91 days of study. Moreover, Eriksson et al[129] reported that a temperature of 53°C caused irreversible tissue injury and that the critical temperature for bone injury lies at 47°C, only 10°C above human body temperature.[130]

A device with the ability to lower pulpal temperatures was studied in monkeys (Macaca mulatta).[131] The pulp chamber temperatures were lowered to 15.5°C and 12.4°C for as long as 20 min. The cooling temperatures generated by the device were found to be within the safe range and not harmful to the pulp.[132,133] Histological examination showed no inflammatory reaction, and this device was considered a possible tool to avoid pulpal inflammation.

The literature on laser heating effects on the pulp is somewhat conflicting. Some authors have reported no pulpal damage with laser irradiation, while others observed various degrees of damage, depending upon the laser used and the power settings of the laser. Lasing has been shown to raise the temperature inside the tooth pulp. The increase in pulp temperature varied as a function of the radiation parameters (energy, pulse frequency, and duration of exposure) and the thickness of dentin remaining over the pulp. Early studies on the biological effects of the ruby laser irradiation demonstrated severe pulpal degeneration of the dental pulp on teeth of experimental animals.[134] These preliminary findings were disappointing concerning the possible use of laser energy for operative procedures on teeth and oral mucosa.

Effects of the Low-level Output Lasers on the Dental Pulp

A comparative in vivo and in vitro study of the thermal effects of four GaAIAs lasers emiting at wavelengths between 750 nm and 905 nm was conducted, to determine temperatures generated during application of these lasers to the cervical region of the teeth. The patients experienced no perceptible stimuli and from the in vitro study, it was demonstrated that the maximum intrapulpal temperature rise was 3°C.[135]

Effects of the Erbium Lasers on the Dental Pulp

Numerous histopathological and immunohistochemical studies have focused on the thermal danger of Er:YAG laser during ablation. The pulp response to Er:YAG laser appears to be similar to the response from high-speed drill application.[136-139] Moreover, the Er:YAG laser was found to lead to pulpal repair earlier than the high-speed drill.[140,141] Er:YAG laser ablation with water cooling prepares enamel and dentin without undesirable temperature changes in the pulp[142-148] and without side effects such as cracks in enamel and dentin.[149] In general, it was concluded that no irreversible damage was seen in the pulp after Er:YAG laser ablation and that the regenerative potential is preserved after ablation.

Similarly, the near-red pulsed Er,Cr:YSGG laser was not found to produce pulpal inflammatory responses when cutting dental hard tissues.[150]

Effects of the Nd:YAG Laser on the Dental Pulp

In a preliminary study by Adrian,[151] the pulp was found to be more resistant to injury by the Nd:YAG laser using the same parameters as the ruby laser in a previous study some years before.[152] In contrast, histological effects of inflammatory responses were seen in Nd:YAG laser exposures two to three times more intense than with the ruby laser.

It seems that the temperature rise, for specific irradiation parameters with Nd:YAG laser, is determined by the tooth thickness, with lower temperature increases associated with a greater dentin thickness.[153,154] The study by White et al[154] indicated the safety laser parameters to avoid a pulpal risk due to temperature increase when 1 mm of remaining dentin is present. Seka et al[155] studied the thermal effect of near-IR (~1000 nm) lasers in dental hard tissues and demonstrated elevated temperatures near the dentino-enamel junction that were considered to endanger the vitality of the pulp several millimeters below the surface.

In a study conducted to measure the dentin permeability after irradiation with Nd:YAG (1064 or 1320 nm wavelength) or Ho:YAG (2100 nm wavelength), all three lasers were found to be effective in reducing the fluid flow. However, the temperature rise was above the safety limits, which indicated that a shorter lasing time and lower power settings must be used in clinical studies.[156] The effects of spot and scanning lasing with a pulsed Nd:YAG laser on cat teeth was also evaluated for the purpose of desensitizing hypersensitive dentin.[157,158] Both studies revealed that irreversible tissue damage to the pulp was produced under the specific parameters used. Subsequently, it was concluded that the clinical application of this laser for the purpose of desensitizing the dentin bears a high risk of severely damaging the pulp tissue.

Nevertheless, an improvement of pulpal blood flow was demonstrated during Nd:YAG laser irradiation, and it appeared that a low energy dose of Nd:YAG laser irradiation can create an antiphlogistic effect.[159] Increased pulpal blood circulation was also demonstrated in the study by Birang et al.[160] Partial oxygen saturation of the pulpal blood increased in the Nd:YAG laser-treated group and was restored to the pretreatment level after a month. Because partial oxygen saturation of the pulpal blood has a direct relationship to dental pulp vitality, it was concluded that the Nd:YAG laser irradiation within the parameters studied caused no irreversible damage to the dental pulp.

Pulpal pressure is another characteristic of pulp physiology which is thought to play a significant role in pulpal inflammation.[161] Pulpal tissue pressure and temperature increased with an increase in the energy power of the laser and a decrease in the thickness of the remaining dentin.

Effects of the CO_2 Laser on the Dental Pulp

Experiments on primates and dogs revealed that low-power CO_2 laser irradiation produces a reactional dentinogenesis without severe inflammatory reactions of the pulp. The formation of reactional dentin could result from an odontoblastic activation caused indirectly by the CO_2 laser.[162,163] In another study, it was possible to perform pulpotomy by CO_2 laser without causing hemorrhage, bacterial contamination, or adverse effects in the radicular portions of pulps that were irradiated.[164]

Launay et al[165] examined the thermal effects of different lasers on enamel, dentin, and pulp tissue. The CO_2 laser produced an elevation of temperature on the enamel surface that reached the melting point of hydroxyapatite. However, the dentin surface temperature did not reach that of enamel, and pulpal overheating was also slight. Similar results were demonstrated in a study by Aniç et al.[166] When they irradiated the dental tissues using specific parameters able to melt the enamel, the temperature rise in the pulp was 4°C, which indicated that thermal injury did not occur.

According to Miserendino et al,[167] CO_2 laser exposures below 10 J were observed to produce temperature increases of less than 5.5°C, which may fall within the range of pulp tolerance according to the study by Zach and Cohen.[126] A few years later, they explored cooling methods to facilitate dissipation of heat generated by CO_2 laser irradiation. Pulsed laser exposure did not seem to slow the increase in intrapulpal temperature. Cooling with an air/water spray, on the other hand, appeared to be an effective method for the prevention of thermal damage.[168]

Bovine teeth were also subjected to CO_2 laser irradiation to study possible pulpal damage.[169] It was demonstrated that when the dentin thickness was less than 3 mm, there was a possibility of thermal injury to the pulp.

CONCLUSION

Since the mechanisms involved in laser treatment of dentin hypersensitivity are relatively unknown, care must be taken to optimize safe and effective treatment. Lasers have been shown to fulfill the requirements of Grossman's criteria by being nonirritating to the pulp when used under specific parameters. The most important issue in laser therapy is to determine the correct parameters for achieving satisfactory results without detrimental thermal pulpal effects, fractures, or carbonization. Complete familiarity with a safe and recommended protocol is essential at all times when irradiating vital teeth with lasers to alleviate the pain associated with hypersensitive dentin.

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