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Authors
Kimura, Y
Arrastio-Jitosho, AMA
Wilder-Smith, P
et al.

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Thermal, Microstructural and Physicochemical Effects of Nanosecond Pulsed Nd : YAG Laser Irradiation on Dentin

YUICHI KIMURA [b,*], ANNA MARIE A. ARRASTIA-JITOSHO [a],
PETRA WILDER-SMITH [a], LIH-HUEI L. LIAW [a], STEPHANIE LIN [a],
KOUKICHI MATSUMOTO [b] and MICHAEL W. BERNS [a]

[a] *Beckman Laser Institute and Medical Clinic, UC Irvine, 1002 Health Sciences Road East, Irvine, CA 92715, USA;* [b] *Department of Endodontics, School of Dentistry, Showa University, 2-1-1 Kitasenzoku, Ohta-ku, Tokyo 145, Japan*

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The effects of nanosecond pulsed Nd:YAG irradiation on crown and root dentin susceptibility to artificial de- and remineralization were investigated. Laser-induced heating and structural effects were also determined. Thirty caries-free extracted human molar teeth were used. One group of 12 teeth was bisected longitudinally, and each surface covered with acid resistant varnish, leaving 4 windows on the cut dentin surface. Using a Q-switched nanosecond pulsed Nd:YAG laser (1064 nm), one half of each tooth was irradiated at one of the following parameters: 3 mm spot size, a fluence of 1.0 J/cm^2. The other half of each tooth served as (non-irradiated) control. All samples were then subjected to a 4 day, thrice daily de- and remineralization cycle. Prior to and after each demineralization, microhardness measurements were taken. After 4 days, samples were again bisected, and the other sample halves used for SEM. Microhardness in the irradiated samples did not differ significantly ($p < 0.01$) compared with controls; SEM results showed some laser-induced alterations on crown and root dentin surfaces. Thermometric measurements on 18 teeth at energy densities of 1.0–4.1 J/cm^2 revealed intrapulpal temperature increases of approximately 2°C at a dentin thickness of 2 mm during irradiation. No consistent effect of Q-switched nanosecond pulsed Nd:YAG laser irradiation on microstructure and de- and remineralization of dentin was determined ($p < 0.01$), but SEM results showed some surface alterations on the irradiated samples.

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* Corresponding author. Tel.: (81)3-3787-1151 (Ext. 247). Fax: (81)3-3787-1229. E-mail: yukimura@hp.dent.showa-u.ac.jp.

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INTRODUCTION

Alterations in enamel caries resistance were first achieved using the ruby laser (Stern and Sognnaes, 1965). Since that time, other lasers, such as the Nd : YAG (1060 nm) or CO_2 (10.6 μm) have also been used to enhance caries resistance in enamel (Fox *et al.*, 1992a,b; Nelson *et al.*, 1986a,b; 1987; Powell *et al.*, 1993; Stern *et al.*, 1972; Stern and Sognnaes, 1972; Yamamoto and Ooya, 1974; Yamamoto and Sato, 1980; Walsh and Perham, 1991). The former laser has been used in various modes to alter caries resistance in enamel (Morioka *et al.*, 1991). A few investigations into laser-induced changes in dentin have also been reported (Dederich *et al.*, 1984; Goodis *et al.*, 1993; Nakayama, 1992; White *et al.*, 1993), but the effects of the Nd : YAG laser on dentin have not been fully defined. Laser energy can be used to affect the microstructure and physico-chemical properties of dentin surfaces (Featherstone and Nelson, 1987). Cooper *et al.* (1988) and Dederich *et al.* (1984) reported surface dentin melting and resolidification into a non-porous glazed surface after application of laser energy. The thermal effects of the laser on the tooth as a vital entity must be considered. An intrapulpal temperature rise measuring as little as 5.5°C can cause irreversible pulp damage (Zach and Cohen, 1965). In previous investigations, heat from irradiation with the Nd : YAG laser at continuous wave or long pulsed settings often caused melting of the intertubular dentin (Wigdor, 1992). Due to the proximity of heat-sensitive pulpal tissues to the dentin, it is important to minimize any temperature increases in dental hard substance during irradiation. The use of short-duration pulsed lasers can achieve significant reductions in the amount of heat generated within a target tissue. Thus, the Q-switched Nd : YAG laser system with nanosecond duration pulses may well offer significant advantages over conventional devices with regard to pulpal heating, due to its short pulse duration and high peak powers. However, to date very few reports exist concerning the effects of Q-switched Nd : YAG laser irradiation on dentin. The purpose of this study was to investigate the effects of the Q-switched Nd : YAG laser emitting nanosecond pulses on crown and root dentin microstructure, microhardness and de- and remineralization characteristics, and to evaluate thermal events during irradiation.

MATERIALS AND METHODS

Sample Preparation

Thirty extracted human teeth showing no clinical sign of caries or decay were selected and stored in demineralized water with 0.01% (w/v) thymol. These teeth were randomly divided into two groups; group A consisted of 12 teeth, group B of 18 teeth. Teeth in group B were used for thermal measurements as described later in this text. The 12 teeth in group A were longitudinally bisected with a low speed saw (Isomet, Buehler, IL, USA), and embedded in acrylic resin (Buehler, IL, USA). The surfaces were polished using a metallurgical apparatus (Buehler, IL, USA) with carbimet paper discs (grits 240, 320, 400, 600) (Buehler, IL, USA) and Metadi diamond suspension (1, 3, 6 micron) on a polishing cloth (Buehler, IL, USA). After polishing, each surface was covered with acid resistant vanish, leaving four 2–3 mm windows on the cut dentin surface.

Laser Device and Laser Irradiation

This study was performed using a Q-switched nanosecond pulse duration Nd:YAG laser (Medlite, Continuum Biomedical, Inc., Livermore, CA, USA). This laser emits at a wavelength of 1064 nm and uses an articulated arm delivery system with a non-contact focusing handpiece; thus no fiber was used.

Group A: All teeth except the control group were subjected to irradiation at the following parameters: energy density of 1.0 J/cm^2, a spot size of 3 mm and a pulse width of 5–10 ns. These parameters were identified after irradiation at a range of parameters in preliminary investigations (Kimura *et al.*, 1997). *Group B*: All teeth were subjected to irradiation at the following parameters: energy densities of 1.0, 2.1, 3.1, 4.1 J/cm^2, a spot size of 3 mm and a pulse of 5–10 ns.

In this investigation, one pulse of laser irradiation was used on each sample. Therefore, fluence and energy density values are identical throughout this paper.

De-/Remineralization

Irradiated and control samples in Group A were subjected to a 4 day de- and remineralization cycle, according to the method of Herkstroter *et al.* (1991). The demineralization solution used contained 3 mM $CaCl_2 \cdot 2H_2O$ (Calcium Chloride Dihydrate), 3 mM KH_2PO_4 (Potassium Phosphate Monobasic), 50 mM CH_3COOH (Acetic Acid) adjusted with KOH (Potassium Hydroxide) to pH 4.5. The remineralization solution consisted of 1.5 mM $CaCl_2 \cdot 2H_2O$, 0.9 mM KH_2PO_4 and 20 mM Hepes (N-2-Hydroxyethylpiperazine N′-2-Ethanesulfonic Acid) at pH 7.0 adjusted with KOH. Demineralization occurred for 30 min; remineralization for 2 h. Demineralization occurred 3 times daily. Prior to and after demineralization, microhardness measurements were taken on one sample half. After 4 days, samples were bisected again, and the half not used for microhardness measurements was examined by LM and SEM.

Mircohardness

The Leitz Miniload II (Ernst Leitz, Germany) microhardness tester was used with an indentation weight of 100 g. Measurements were taken on samples in Group A each time at six locations per window. The measured indentation lengths were converted to Knoop hardness values and microhardness was expressed as percentage of original sample hardness. Statistical analyses were performed by paired Student's *t*-test (two-tailed).

SEM

Samples in Group A were treated with NaOCl (Sodium Hypochlorite) (5.25% by wt) for one hour and dehydrated in a graded series of aqueous ethanol (30, 50, 70, 90, 100% ethanol) for 10 min at each concentration, mounted on stubs using colloidal silver liquid (Ted Pella, CA, USA) and gold coated on a PAC-1 Pelco advanced coater

9500 (Ted Pella, CA, USA). Micrographs of the dentin were taken on a Philips 515 (Mohawk, NJ, USA) SEM.

Thermal Measurements

Enamel and cementum were removed from the 18 teeth in Group B, which were then bisected perpendicular to the long axis of the dentinal tubules. After sample preparation, one thermosensor with a 1.25 mm diameter (Omega, Stamford, CT, USA) (#1) was inserted to contact snugly the inside root canal wall, and centered behind the middle of the target irradiation area. A second thermosensor (#2) was placed inside the root canal 1.5 mm lateral to the outer margin of the laser beam. Thermosensors were attached to a Miniature Cold Junction Compensator (Omega, Stamford, CT, USA) allowing calibration of temperature measurements. The external tooth surface was irradiated with the beam impinging perpendicularly at the parameters described above (Fig. 1). Statistical analyses were performed by paired Student's *t*-test (two-tailed).

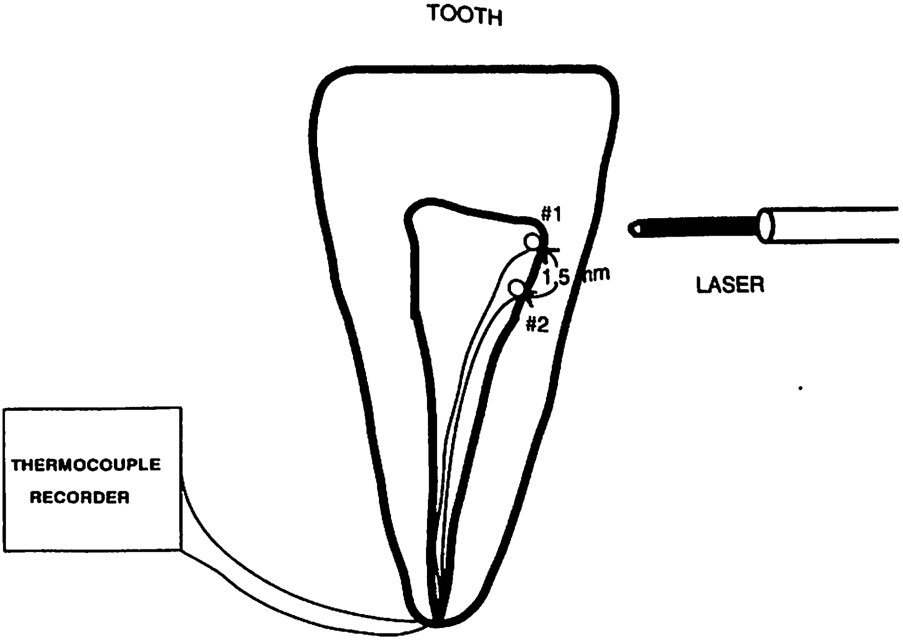

FIGURE 1 Temperature measurements set-up.

RESULTS

De-/Remineralization

Microhardness values as percentage of original sample hardness during a 4 day de- and remineralization cycle are depicted in Fig. 2. Figure 2(a) shows results for crown dentin, and Fig. 2(b) shows results for root dentin. Microhardness of irradiated samples did not differ significantly from that of controls ($p < 0.01$). Results for crown and root dentin were almost identical ($p < 0.01$). Microhardness of irradiated samples did not differ significantly from that of controls ($p < 0.01$). No significant difference was determined between results for crown and root dentin ($p < 0.01$) except at R7 (control sample). Throughout the course of this study, after de- and remineralization, microhardness of all dentin samples decreased gradually, sometimes in a zigzag pattern, and finally measured approx. 30% of original hardness after 4 days.

SEM results showed some alterations on the irradiated surfaces of crown and root dentin. Figure 3 shows the SEM results for crown dentin of control samples (a) and laser treated specimens (b). The

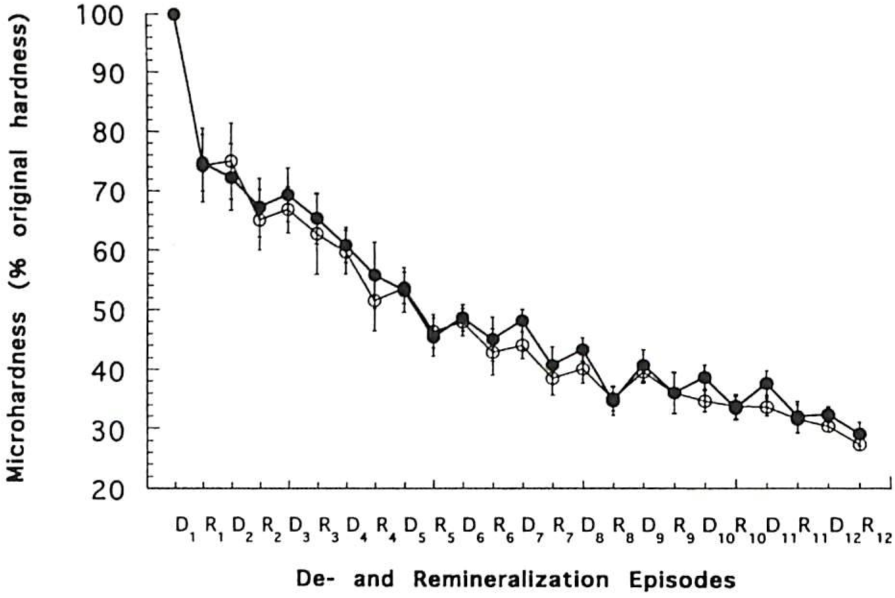

FIGURE 2(a)

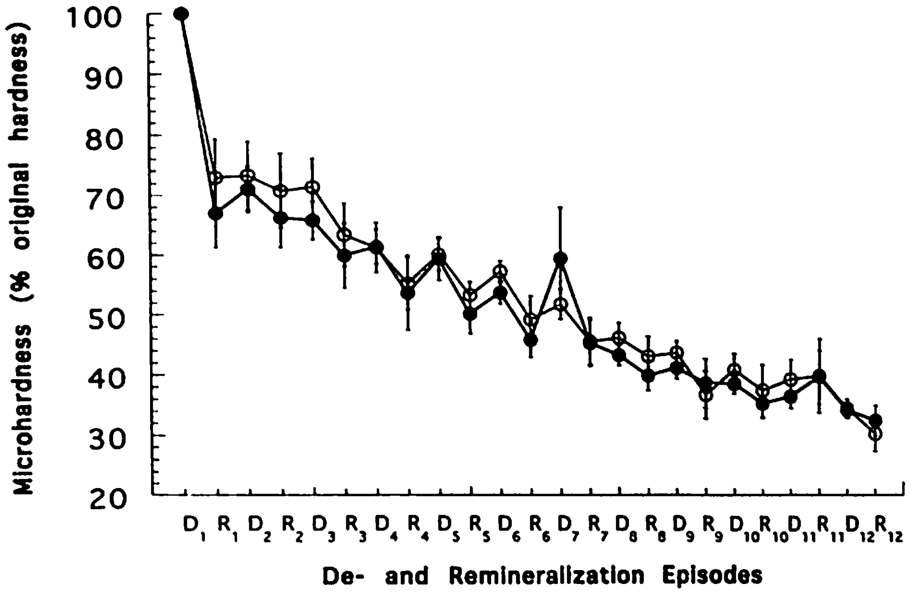

FIGURE 2(b)

FIGURE 2 Microhardness measurements on crown dentin (a) and root dentin (b). (o) represents values for control samples, and (●) represents irradiated specimens (1 J/cm^2). All samples were subjected to a 4 day de- and remineralization cycle. Demineralization occurred 3 times daily. Prior to and after demineralization, microhardness measurements were taken. Data shown represent the mean of 6 measurements per site per event, in 6 samples, expressed as percentage of original hardness and standard error of the mean.

surfaces of irradiated samples were partially melted and smooth; some of dentin tubules were narrowed compared with the controls while some were completely closed. Figure 4 shows the SEM results in root dentin of control samples (a) and laser treated specimens at 1.0 J/cm^2 (b). The surfaces of irradiated samples appeared partially melted and smooth, and some of dentin tubules were also narrowed and closed compared with the control group.

Thermal Effects

Figure 5 shows thermocouple traces behind the central irradiation site during irradiation of a horizontally sectioned tooth crown at 1.0 J/cm^2. A sharp temperature increase was observed within a fraction of a second after commencement of irradiation. Depending on

FIGURE 3(a)

FIGURE 3(b)

FIGURE 3 Micrographs showing crown dentin of control (a) and laser treated (b) (1 J/cm^2) samples. Dentin tubules appear narrowed or closed in irradiated samples compared to control samples. Magnification is ×2100. Bar represents 10 µm.

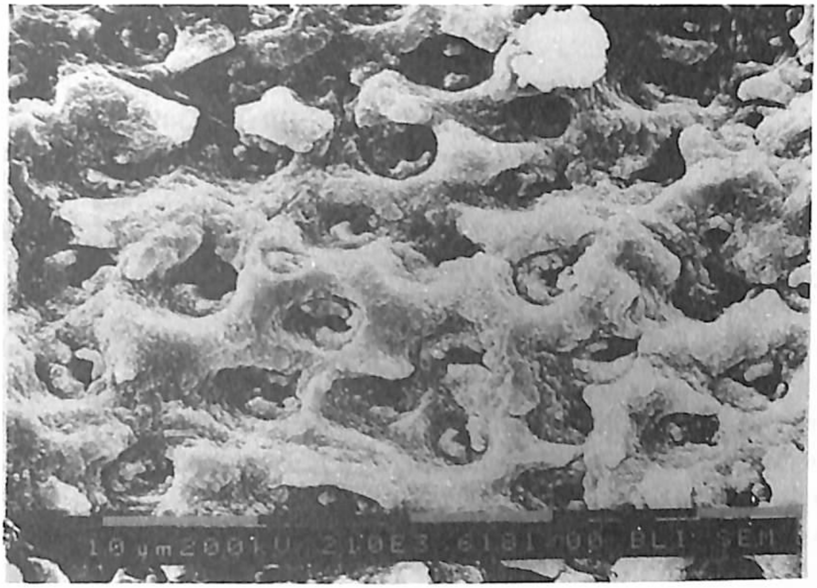

FIGURE 4(a)

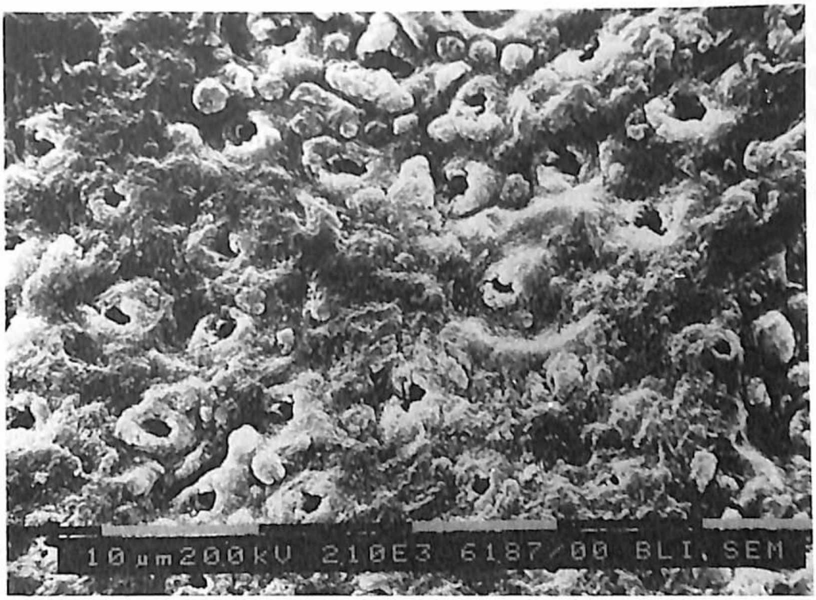

FIGURE 4(b)

FIGURE 4 Micrographs showing root dentin of control (a) and laser treated (b) (1 J/cm^2) samples. Dentin tubules appear narrowed or closed in irradiated samples compared to control samples. Magnification is ×2100. Bar represents 10 µm.

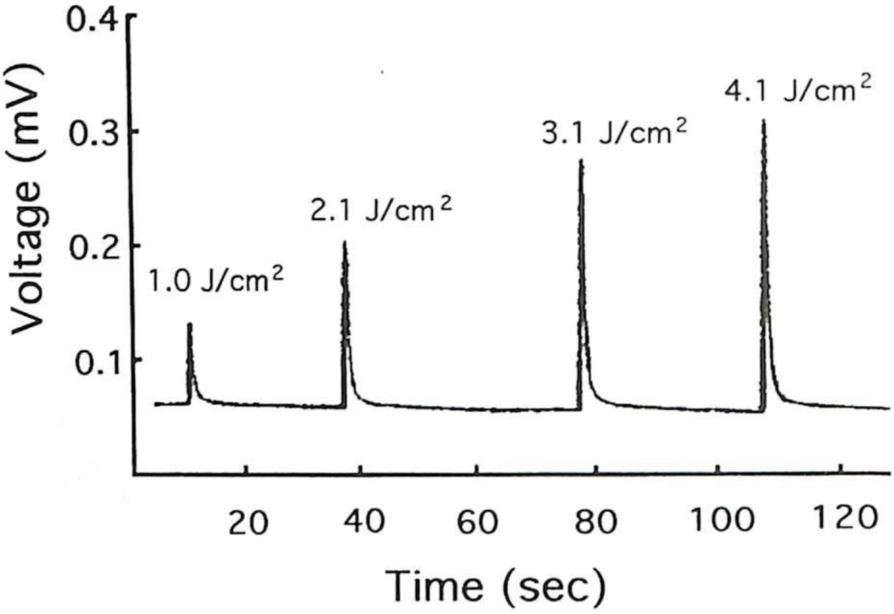

FIGURE 5 Trace of thermocouple measurement. Beginning from the left side of the figure, exposures at 1.0, 2.1, 3.1, 4.1 J/cm^2, respectively, are indicated. In this sample, dentin thickness measured 1.7 mm. Horizontal bar represents a time interval, and vertical bar represents a deflection of voltage.

TABLE I Relation of temperature increase to dentin thickness at 1 J/cm^2

	Dentin thickness (mm)	*Temperature increase* (°C)
Crown dentin	1.71–1.97	0.54–2.44
Root dentin	1.73–2.02	0.14–1.70

Values show the results in horizontal sections.
Five–six samples were used per measurement, and minimum and maximum values are shown.

the dentin thickness and energy density applied, temperature increases differed. At approx. 2 mm dentin thickness and an energy density of 1.0 J/cm^2, temperature increases directly behind the central irradiation site measured < 2.5°C (Table I) and lasted < 2 s. Table I shows the temperature increase results in the thermosensor behind the center of the irradiation site in horizontal sections of teeth.

Thermal results on crown or root dentin did not differ significantly ($p < 0.01$). During irradiation, temperature increases at the thermocouple sensor located 1.5 mm lateral to the laser beam did not exceed 0.1°C.

DISCUSSION

The Q-switched mode with nanosecond pulse duration offers the advantage of minimizing potential pulpal temperature increases due to the short pulse duration. This is particularly important when dentin is the target tissue, because dentin lies in a closer proximity to the pulp than enamel and because of the ease of thermal propagation through the tubular dentin structure. However to date almost no reports exist concerning the effects of Q-switched Nd:YAG laser irradiation on dentin.

In a previous preliminary investigation, the approximate threshold values for ablation and microstructural damage to dentin using this device were determined. Energy densities $> 5.4\,\mathrm{J/cm^2}$ were found to cause outright ablation of tooth substance (Kimura *et al.*, 1997). In other investigations, higher average energy densities were identified as the ablation threshold, perhaps due to the much lower peak powers produced by the longer-pulsed devices used in those studies (Ito *et al.*, 1993; Morlock *et al.*, 1992; White *et al.*, 1993). In this investigation, after irradiation at an energy density of $1.0\,\mathrm{J/cm^2}$, and a spot size of 3 mm, no obvious structural changes were visible in the light microscope before or after de- and remineralization. Using SEM, however, the cumulative microstructural effects of artificially induced de- and remineralization were clearly evident in all samples. After a 4 day cycle, surfaces of control samples were rough, and dentin tubules were open. In contrast, surfaces of irradiated samples appeared partially melted and smoother than the control samples, and some dentin tubules were narrowed, or closed. The percentage of tubules that appeared closed or narrowed varied within and between samples, partly due to localized variation in tubule orientation. According to previous reports (Dederich *et al.*, 1984; Levy, 1992), Nd:YAG laser irradiation of dentin with longer pulse durations than those used in this investigation causes surface melting closure of dentin tubules, and sometimes also produces visible calcification structures. No such calcifications, however, were observed in our study. This may be due to the different parameters used. In our investigation, only a single very short pulse of laser irradiation was used at relatively low energy densities, as opposed to the long-duration irradiation in the continuous wave or long-pulsed mode used in other investigations, which would induce far higher temperature rises in target tissues.

Use of microhardness techniques in this study had its limitations. With increasing de- and remineralization, measurement variability increased significantly. Similar observations have been reported by other authors (Arends and ten Bosch, 1992; Manning and Edgar, 1992; White *et al.*, 1992), and are attributed to greater surface roughness and dissolution after prolonged de- and remineralization. Within the limitations of the technique, we could determine no consistent effect of laser irradiation on de- and remineralization of dentin. Temperatures as measured by thermocouple behind the central irradiation site increased by an average 2.0°C during irradiation. Duration of the temperature increase induced by a pulse of Nd:YAG laser irradiation in our investigation was very short (less than 2 s). The temperatures measured in the central thermocouple were at least in part a measure of heat generated by direct irradiation of the thermocouple. Despite this factor, temperature rises measured by this thermocouple were very small and transient. Heat conduction through the dental tissues was minimal, as minimal or no thermal effects (<0.1°C) were determined in the thermocouple located 1.5 mm lateral to the irradiated site.

According to Zach and Cohen (1965), temperature increases exceeding 5.5°C for 5–20 s can cause irreversible changes in the pulp. Thus, the temperature increases measured in our study appear to lie well below the threshold of pulpal damage. Temperature increases within the root canal are related to factors such as dentin thickness, energy densities, and dentinal tubule orientation. Our results indicate that at a dentin thickness greater than 2 mm and energy densities of 1.0 J/cm^2, laser-induced thermal events might be well tolerated by pulpal tissues. However, effects of multiple pulses should still be investigated. In contrast, other investigations using much longer pulse durations at this wavelength reported that the pulpal thermal damage threshold can be easily reached or exceeded (von Fraunhofer and Allen, 1993; Sugata *et al.*, 1994).

In conclusion, we were unable to detect any significant caries-preventive effect of nanosecond pulse duration Nd:YAG laser irradiation at sub-ablation parameters on crown and root dentin. However, some interesting microstructural effects were achieved and relatively low temperature rises were documented during irradiation.

Acknowledgments

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References

Arends, J. and ten Bosch, J.J. Demineralization and remineralization evaluation techniques. *J. Dent. Res.* **71**(Spec Iss), 924–928, 1992.

Cooper, L.F., Myers, M.L., Nelson, D.G.A. and Mowery, A.S. Shear strength of composite bonded to laser-pretreated dentin. *J. Prosthet. Dent.* **60**, 45–49, 1988.

Dederich, D.N., Zakariasen, K.L. and Tulip, J. Scanning electron microscopic analysis of canal wall dentin following neodymium-yttrium-aluminum-garnet laser irradiation. *J. Endodon.* **10**(9), 428–431, 1984.

Featherstone, J.D.B. and Nelson, D.G.A. Laser effects on dental hard tissue. *Adv. Dent. Res.* **1**, 21–26, 1987.

Fox, J.L., Yu, D., Otsuka, M., Higuchi, W.I., Wong, J. and Powell, G.L. The combined effects of laser irradiation and chemical inhibitors on the dissolution of dental enamel. *Caries Res.* **26**, 333–339, 1992a.

Fox, J.L., Yu, D., Otsuka, M., Higuchi, W.I., Wong, J. and Powell, G.L. Initial dissolution rate studies on dental enamel after CO_2 laser irradiation. *J. Dent. Res.* **71**, 1389–1397, 1992b.

Goodis, H.E., White, J.M., Marshall, S.J. and Marshall, G.W. Jr. Scanning electron microscopic examination of intracanal wall dentin hand versus laser treatment. *Scanning Microsc.* **7**(3), 979–987, 1993.

Herkstroter, F.M., Witjes, M. and Arends, J. Demineralization of human dentine compared with enamel in a pH-cycling apparatus with a constant composition during de- and remineralization periods. *Caries Res.* **25**, 317–322, 1991.

Ito, K., Nishikata, J. and Murai, S. Effects of Nd:YAG laser radiation on removal of a root surface smear layer after root planing: A scanning electron microscopic study. *J. Periodontol.* **64**(6), 547–552, 1993.

Kimura, Y., Wilder-Smith, P., Arrastia, A.M.A., Liaw, L-H.L., Matsumoto, K. and Berns, M.W. Effects of nanosecond pulsed Nd:YAG laser irradiation on dentin resistance to artificial caries-like lesions. *Lasers Surg. Med.* **20**, 15–21, 1997.

Levy, G., Cleaning and shaping the root canal with a Nd:YAG laser beam: A comparative study. *J. Endodon.* **18**, 123–127, 1992.

Manning, R.H. and Edgar, W.M. Intra-oral models for studying de- and remineralization in man: Methodology and measurement. *J. Dent. Res.* **71**(Spec Iss), 895–900, 1992.

Morioka, T., Tagomori, S. and Inai, Y. An incremental effect of acid resistance and remineralization on incipient caries of enamel with laser irradiation. *J. Jpn. Soc. Laser Dent.* **2**, 1–9, 1991.

Morlock, B.J., Pippin, D.J., Cobb, C.M., Killoy, W.J. and Rapley, J.W. The effect of Nd:YAG laser exposure on root surfaces when used as an adjunct to root planing: An *in vitro* study. *J. Periodontol.* **63**(7), 637–641, 1992.

Nakayama, T. A morphological study on the enamel and dentine irradiated by pulsed Nd:YAG laser. *J. Jpn. Soc. Laser Dent.* **3**, 57–64, 1992.

Nelson, D.G.A., Shariati, M., Glena, R., Shields, C.P. and Featherstone, J.D.B. Effect of pulsed low energy infrared laser irradiation on artificial caries-like lesion formation. *Caries Res.* **20**, 289–299, 1986a.

Nelson, D.G.A., Jongebloed, W.L. and Featherstone, J.D.B. Laser irradiation of human dental enamel and dentine. *NZ Dent. J.* **82**, 74–77, 1986b.

Nelson, D.G.A., Wefel, J.S., Jongebloed, W.L. and Featherstone, J.D.B. Morphology, histology and crystallography of human dental enamel treated with pulsed low-energy infrared laser radiation. *Caries Res.* **21**, 411–426; 1987.

Powell, G.L., Yu, D., Higuchi, W.I. and Fox, J.L. Comparison of three lasers on demineralization of human enamel. *SPIE Proceedings* **1880**, 188–192, 1993.

Stern, R.H. and Sognnaes, R.F. Laser effect on dental hard tissue. *J. So. Cal. Assoc.* **33**, 328–329, 1965.

Stern, R.H., Vahl, J. and Sognnaes, R.F. Lased-enamel: Ultrastructural observation of pulsed carbon dioxide laser effects. *J. Dent. Res.* **51**, 455–460, 1972.

Stern, R.H. and Sognnaes, R.F. Laser inhibition of dental caries suggested by first tests *in vivo*. *J.A.D.A.* **85**, 1087–1090, 1972.

Sugata, F., Ohmori, K., Tanaka, T., Yuuzu, T., Senda, A., Gomi, A., Kamiya, K. and Hasegawa, J. The effect of CO_2 laser irradiation on dentin. *J. Jpn. Soc. Laser Dent.* **5**, 73–80, 1994.

Yamamoto, H. and Ooya, K. Potential of yttrium-aluminum-garnet laser in caries prevention. *J. Oral Path.* **3**, 7–15, 1974.

Yamamoto, H. and Sato, K. Prevention of dental caries by Nd:YAG laser irradiation. *J. Dent. Res.* **59**, 2171–2177, 1980.

von Fraunhofer, J.A. and Allen, D.J. Thermal effects associated with the Nd/YAG dental laser. *Angle Orthod.* **63**(4), 299–304, 1993.

Walsh, L.J. and Perham, S.J. Enamel fusion using a carbon dioxide laser: A technique for sealing pits and fissures. *Clin. Prev. Dent.* **13**(3), 16–20, 1991.

White, D.J., Faller, R.V. and Bowman, W.D. Demineralization and remineralization evaluation techniques – added considerations. *J. Dent. Res.* **71**(Spec Iss), 929–933, 1992.

White, J.M., Goodis, H.E., Marshall, G.W. Jr. and Marshall, S.J. Identification of the physical modification threshold of dentin induced by neodymium and holmium YAG lasers using scanning electron microscopy. *Scanning Microsc.* 7(1), 239–246, 1993.

Wigdor, H.A. Study investigates effects of three lasers on dental hard tissue. *Biomedical Optics* **1**(2), 1, 1992.

Zach, L. and Cohen, G. Pulp response to externally applied heat. *Oral Surg.* **19**, 515–530, 1965.