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Authors
Wilder-Smith, P
Nguyen, A
Lin, S
et al.

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Original Articles

Effects of Cavity Preparation Using a Nanosecond-pulsed Nd-YAG Laser on Tooth–Restoration Interface

P. WILDER-SMITH, A. NGUYEN, S. LIN, M.W. BERNS

Beckman Laser Institute & Medical Clinic, University of California, Irvine, CA 92612, USA

Correspondence to: P. Wilder-Smith, Director of Dentistry and Assistant Professor, Beckman Laser Institute and Medical Clinic, 1002 Health Science Road East, University of California, Irvine, CA 92612, USA

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Abstract. This study evaluated the tooth–restoration interface between composite resin or glass ionomer cement and the tooth surface in teeth where caries removal and cavity preparation were performed either with the dental drill, the dental drill and laser irradiation, or laser irradiation alone. A nanosecond-pulsed Nd-YAG laser was used at energy densities of 2–8 J cm^{-2}. After tooth restoration, microleakage tests were performed using methylene blue. Using general linear model procedures, no significant differences in microleakage were determined between 'drill' and 'drill and laser'-prepared groups ($p<0.01$) in resin- and in glass-ionomer-restored teeth. These specimens showed significantly less dye penetration than the 'laser only' group ($p<0.0001$). No correlation was found between fluence and microleakage using either restorative material ($p=0.8$). Dye penetration was significantly greater in the composite-filled than in the glass-ionomer group ($p<0.05$). Mechanisms influencing laser effects on bonding require further investigation before clinical application of lasers as an alternative to the dental drill can become viable.

INTRODUCTION

A wide range of lasers have been investigated for their ability to ablate healthy and carious hard dental tissues (1–15). However, before laser ablation of hard dental tissues can become clinically viable, several issues pertaining to safety and efficacy of procedures need to be resolved.

Laser–tissue interactions using the devices currently available to clinicians are dominated by the absorption characteristics of light. Laser radiation, absorbed in the surface layers, heats and melts/vaporizes the target tissues. Vaporization creates a recoil momentum which ejects liquified substrate in a secondary ejection process. The laser beam's depth of penetration, which is related to the tissues' optical properties, becomes very relevant when, for example, enamel or dentin are the primary targets for irradiation, and yet the laser beam has the potential to penetrate through these tissues to affect the underlying pulpal tissues as well. The choice of laser parameters is also vital; in general, longer pulse durations are less desirable from the thermal aspect, as they allow thermal energy to accumulate and penetrate sufficiently deeply into the target tissue to induce both direct damage and thermo-mechanical stresses. As a consequence, collateral damage can occur.

Pulpal tissues are particularly sensitive to thermal events (16), whereas dental hard tissues undergo cracking, cratering, fracture, structural breakdown or melting in response to high temperatures (17–21). Pulse shortening results in smaller volume heating due to the reduced energy deposition time, and the threshold energy for ablation decreases as well (22–23). Thus, short laser pulses can result in reduced collateral, thermal and structural damage. Thermal studies performed using the nanosecond-pulsed Nd-YAG laser have indeed demonstrated the capability of this laser to ablate dentin with reduced thermal effects in adjacent dental tissues (22, 24–26), as compared with those of conventional Nd-YAG lasers available to dental clinicians.

Another issue involves potential deleterious laser-induced alterations in the tooth surface which may, for example, prevent successful bonding of restorative materials to the irradiated surfaces. Such factors include irradiation-induced melting, cratering, charring or cracking and chemical changes in surface composition (17–21, 27–31). The capability for complete caries removal must also be evaluated.

An intact interface acting as a barrier to microleakage of bacteria and oral fluids is important in preventing dental pathology and pain. Several researchers have investigated the use of lasers for intentional modification of tooth surfaces to improve the tooth surface–restoration interface. In these studies, lasers were usually used solely for surface treatment after conventional cavity preparation (32–41). Most of these investigations were performed using fairly long-pulsed or continuous wave Nd-YAG or CO_2 lasers, which would tend to induce significant temperature increases during irradiation, giving rise to concerns about pulpal tolerance of such procedures. Moreover, the results obtained in these studies varied enormously, ranging from laser-enhanced bonding of dentin with composite resins (40), to marginal microleakage attributed to the effects of laser irradiation (32, 33). This wide range of results demonstrates that further investigation and quantification of the issues involved is necessary prior to clinical application of lasers to restorative procedures. Cost/benefit factors should also be considered; dental lasers are currently still fairly expensive devices. Therefore, it may be more useful to investigate the tooth–restoration interface after laser use for actual cavity preparation, instead of merely applying such a costly device as an adjunct for minor modification of the surface of conventionally prepared cavities.

This study was performed to evaluate the tooth–restoration interface created between a composite resin or a glass ionomer cement and the tooth surface in teeth where caries removal and cavity preparation were performed either conventionally or using the nanosecond-pulsed Nd-YAG laser. In the drill-prepared group, one half of the samples were additionally irradiated to investigate laser-induced surface modifications and their effects on bonding.

MATERIALS AND METHOD

Laser device

The Nd-YAG laser (Medlite, Continuum Biomedical Inc., Santa Clara, CA, USA) emitted at a wavelength of 1064 nm; pulse durations approximated 5–10 ns. Light was delivered through an articulated arm and an adjustable handpiece, with a spot size of 2 mm. The device was used in the non-contact mode.

Tooth sample preparation

A total of 104 teeth was used in this study. Fifty-two teeth were filled with composite resin; all samples in this group were allocated to Group 1. Teeth in Group 1 were prepared for composite-resin restoration either using the drill alone (Group 1A), using the laser alone (Group 1B), or using drill and laser (Group 1C). A further 52 specimens were filled with glass ionomer cement and allocated to Group 2. Teeth in Group 2 were prepared for glass-ionomer restoration either using the drill alone (Group 2A), using the laser alone (Group 2B), or using drill and laser (Group 2C). The experimental scheme within each group of 52 teeth is shown in Fig. 1.

Class II lesions and composite resin

Sample preparation. Fifty-two extracted permanent human teeth with clinical evidence of class II decay were used for this section of the study. In an attempt to gather similar samples, only teeth with darkly discoloured carious dentin and no gross structural cavitation or destruction as determined by the naked eye were included. These teeth were randomly divided into three groups as described below and in Fig. 1.

Group 1A: Caries was removed in seven teeth, and class II cavity preparations were performed using the high-speed dental drill with carbide burs and water spray according to conventional technique. Two teeth were examined by light microscopy and scanning electron microscopy (SEM); five teeth were restored, then subjected to dye-penetration testing.

Group 1B: In 24 samples, caries was removed and class II cavity preparations were performed using the Nd-YAG laser. Eight teeth were irradiated at 2, 5 or 8 J cm^{-2},

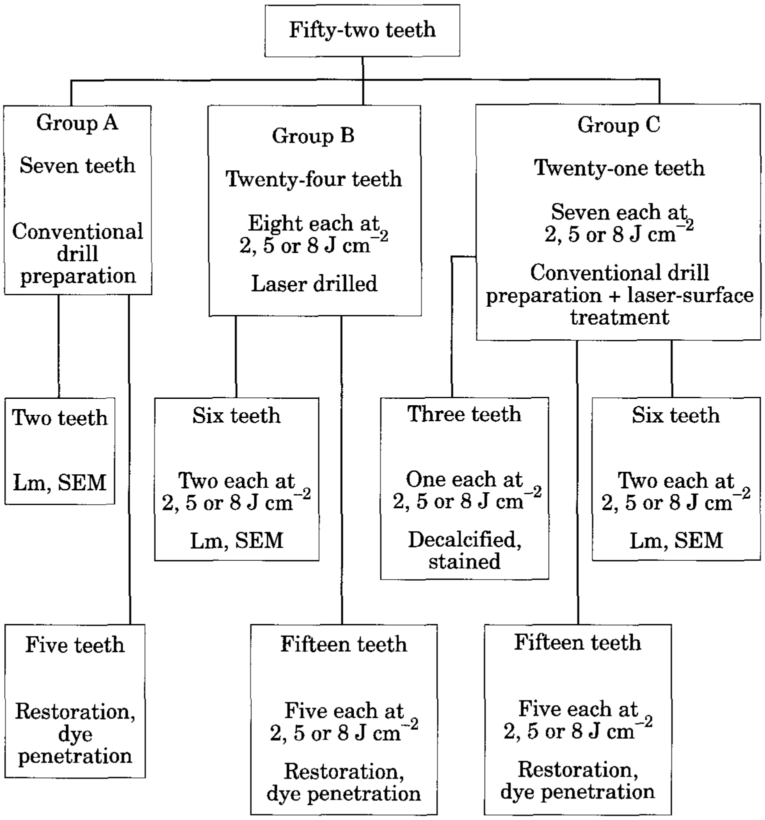

Fig. 1. Study design and sample allocation. SEM, scanning electron microscopy; Lm, light microscopy.

respectively. Two teeth from each of these subgroups (total of six teeth) were subjected to light microscopy and SEM. One sample from each subgroup (total of three teeth) was routinely decalcified and stained with basic fuchsin. Five teeth from each subgroup (total of 15 teeth) were restored, then underwent dye-penetration testing.

Group 1C: Twenty-one samples were prepared with the dental drill as for Group A. Seven teeth were irradiated at 2, 5 or 8 J cm^{-2}, respectively. Two teeth from each of these subgroups (total of six teeth) were subjected to light microscopy and SEM. Five teeth from each subgroup (15 teeth) were restored, then underwent dye-penetration testing.

Laser parameters. For caries removal in the samples belonging to Group 1B, fluences of 2, 5 or 8 J cm^{-2} were used at a frequency of 5 Hz and a spot size of 2 mm. These fluences were selected for practical reasons: 2 J cm^{-2} appeared to the naked eye to approximate the lowest fluence producing any signs of caries ablation; fluences exceeding 8 J cm^{-2} caused excessive acoustic effects and manifestations of burning and charring. Eight samples were irradiated at each of these fluences. Irradiation durations measured from 60 to 205 s. Irradiation was stopped repeatedly to assess the progress of caries removal. Irradiation was performed until no more decay could be removed; this was assessed by visual and tactile inspection. Also, flashes and acoustic effects became minimal at this endpoint.

Samples in Group 1C were subjected to the same laser parameters after conventional (drill) cavity preparation; the laser beam was scanned manually and uniformly over each sample for a total duration of 5 s.

Restoration. Five samples from each subgroup were restored using hybrid composite resin. After cavity preparation, surfaces were rinsed with water. The samples were then air-dried for 10 s. Prisma VLC DYCAL base/liner was applied and polymerized according to manufacturer's instructions. The enamel was acid-conditioned with a caulk conditioner gel (37% phosphoric acid) for 60 s, rinsed with water for 15 s, and Probond primer was applied. Probond Adhesive was applied, cured for 20 s and the cavity was filled incrementally with Prisma A.P.H. Hybrid Composite (Dentsply International Inc., Milford, DE 19963-0359). Using coarse (#1982M), medium (#1982F) and fine (#1982) Sof-Lex Pop-On polishing discs, restorations were trimmed and polished.

Class V lesions and glass ionomer cement

Sample preparations. Fifty-two extracted permanent teeth with cervical lesions measuring approximately 1–2 mm (height) × 2–4 mm (width) × 1–2 mm (depth) were randomly allocated to one of three subgroups as described above (Fig. 1). In an attempt to provide a certain modicum of homogeneity in these samples, only teeth with moderate discolouration and surface softening were included.

Class V, V-shaped, non-retentive cavity preparations were made using the high-speed dental drill with a No. 1700 carbide bur and water spray in Groups 2A and 2C, and using the laser in Group 2B. Samples in Group 2C received laser irradiation after conventional preparation.

Laser parameters. Fluences of 2, 5 or 8 J cm^{-2} were used at a frequency of 5 Hz and a spot size of 2 mm. For cavity preparation in Group 2B, irradiation durations measured 52.6–64.6 s. Irradiation was continued until no further ablation was achieved as determined by direct visual and tactile assessment. This ablation endpoint was visually apparent; flashes and acoustic effects became minimal, with no further progress in caries removal. For samples in Group 2C, the laser beam was scanned manually over each sample for a total duration of 5 s.

Restoration. After irradiation, all the cavity surfaces were cleansed with KETAC dentin conditioner for 10 s, rinsed with water for 30 s, and air-dried for 10 s. The KETAC-FIL was prepared, applied, polymerized and glazed according to manufacturer's instructions. Sof-Lex Pop-On polishing discs beginning from the coarse disc (#1982M), progressing to the medium disc (#1982F) and to the fine disc (#1982) were used for trimming and polishing.

Scanning electron microscopy

Two samples from each subgroup were observed using light microscopy, then prepared for SEM. The specimens underwent dehydration in a graded series of aqueous ethanol (30, 50, 70, 90, 100%) for 10 min at each concentration. Samples were mounted on stubs using colloidal silver liquid (Ted Pella, CA) and gold coated on a Pac-1 Pelco advanced coater 9500 (Ted Pella, CA). Scanning electron micrographs were taken on a Phillips 515 SEM (Mohawk, NJ).

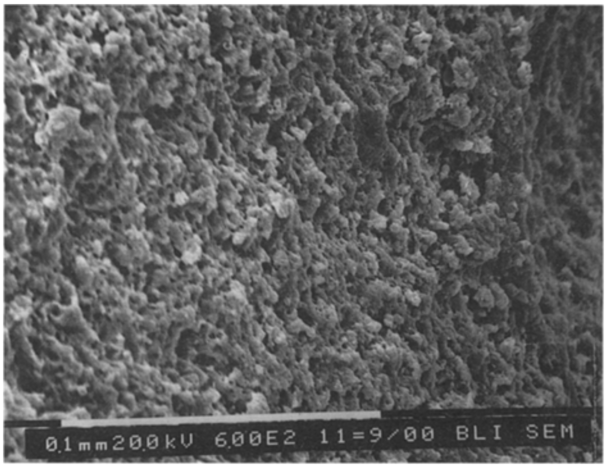

Fig. 2. Scanning electron microscope showing residual caries after laser ablation only at a fluence of 5 J cm^{-2} (×600).

Dye-penetration tests

The five restored specimens from each subgroup were immersed in a 5% methylene blue dye for 4 h as described by Kaplan et al (49), then split into two sections. Dye penetration was measured from the prepared tooth surface to the furthest extent of the dye discolouration in dentin at 10 standardized locations per tooth, using an Olympus light microscope (Olympus Optical Co., Ltd, Japan), as described by Kaplan et al (49).

Statistics

Results were statistically assessed using general linear model procedures.

RESULTS

Class II lesions and composite resin

Caries ablation was quicker at the higher fluences used, but a complete removal of carious tooth substance was not achieved by laser irradiation at any laser parameters. To the naked eye, a residual layer of softened and discoloured tooth substance was apparent. Light microscopy and SEM confirmed these findings (Fig. 2). In the SEM, surfaces of samples irradiated at a fluence of 2 or 5 J cm^{-2} after drill preparation (Fig. 3) resembled those

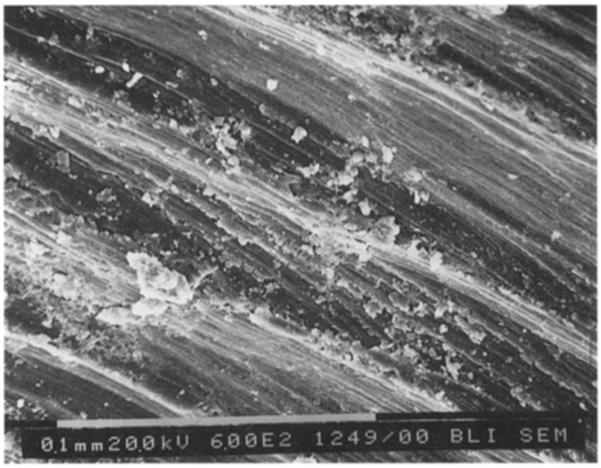

Fig. 3. Scanning electron microscope of dentin surface after conventional drill preparation and laser irradiation at a fluence of 5 J cm^{-2} (×600).

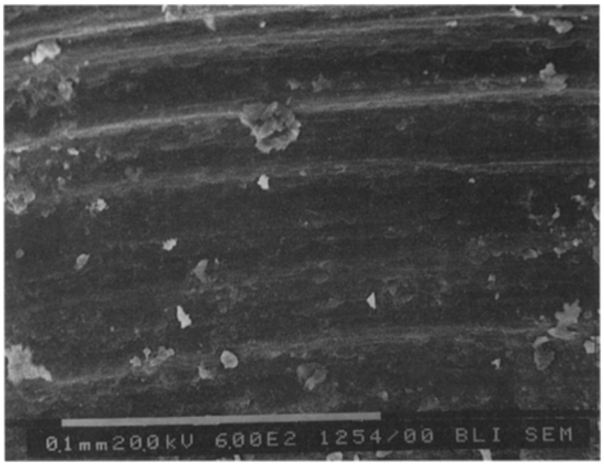

Fig. 4. Scanning electron microscope of dentin surface after conventional drill preparation alone (×600).

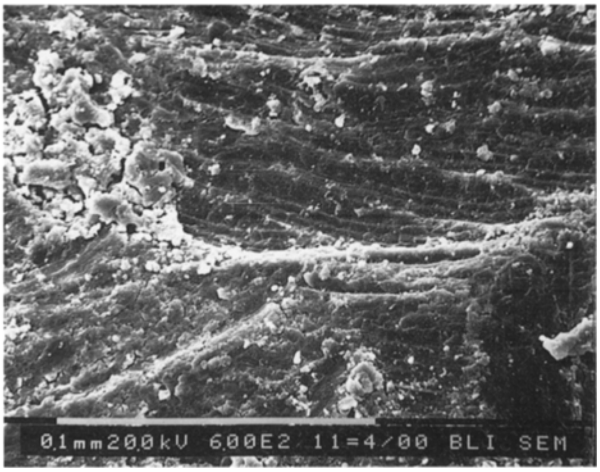

Fig. 5. Scanning electron microscope of dentin surface after conventional drill preparation and laser irradiation at a fluence of 8 J cm^{-2} (×600).

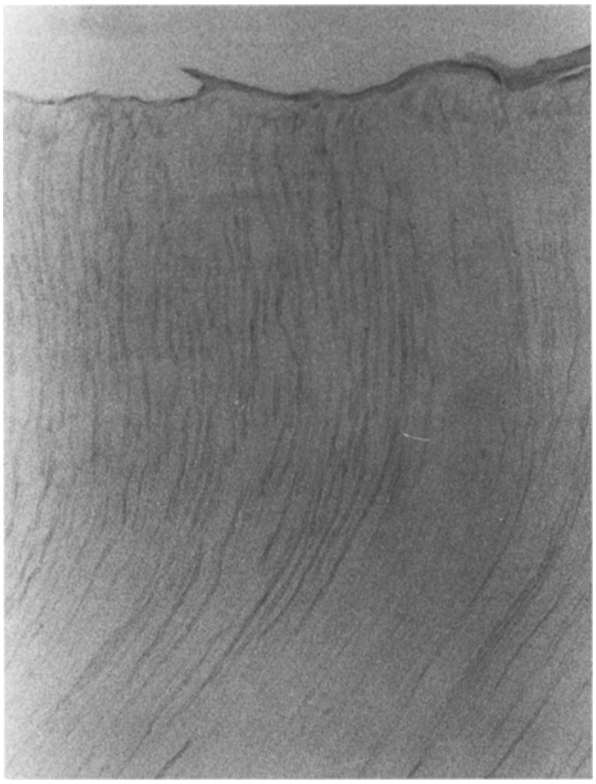

Fig. 6. Cavity surface after laser preparation at a fluence of 5 J cm^{-2} (x335) viewed by light microscopy.

prepared by drill alone, as no morphological changes were apparent (Fig. 4). Irradiation at a fluence of 8 J cm^{-2} after drilling produced a few very minor areas of surface alteration which were mainly noticeable in superficial dentin fragments or debris (Fig. 5). Decalcified and stained samples showed residual infected decay in all specimens where caries removal had been performed using the laser alone (Fig. 6).

Results of dye-penetration measurements are depicted in Table 1. No dye discolouration was recorded within the composite restorations, which microscopically looked more homogeneous than the glass-ionomer restorations. No significant differences in microleakage were determined between the 'drill'- and the 'drill and laser'-prepared groups ($p<0.01$). Drill-prepared specimens without or with subsequent laser irradiation showed significantly less dye penetration than the laser-ablated group ($p<0.0001$). No correlation was found between the fluences used and microleakage in either Group B or Group C ($p=0.8$). It should be noted that standard deviations were relatively high in all groups.

Table 1. Dye-penetration measurements (composite restoration)

Sample preparation	Sample number	Dye penetration (μm)
Drill alone	5	141.5 ± 225.0
Laser (2 J cm^{-2})	5	811.5 ± 517.0
Laser (5 J cm^{-2})	5	667.5 ± 406.0
Laser (8 J cm^{-2})	5	750.5 ± 369.5
Drill and laser (2 J cm^{-2})	5	202.5 ± 139.5
Drill and laser (5 J cm^{-2})	5	112.5 ± 148.0
Drill and laser (8 J cm^{-2})	5	220.0 ± 195.5

Table 2. Dye-penetration measurements (glass-ionomer restoration)

Sample preparation	Sample number	Dye penetration (μm)
Drill alone	5	54.5 ± 66.0
Laser (2 J cm^{-2})	5	318.0 ± 448.0
Laser (5 J cm^{-2})	5	319.5 ± 463.0
Laser (8 J cm^{-2})	5	471.5 ± 586.5
Drill and laser (2 J cm^{-2})	5	61.0 ± 84.5
Drill and laser (5 J cm^{-2})	5	68.0 ± 75.0
Drill and laser (8 J cm^{-2})	5	52.0 ± 69.0

Class V lesions and glass ionomer cement

Results of caries ablation paralleled those described above. Results of dye-penetration measurements are depicted in Table 2. These results also parallel those described above, except that some glass-ionomer restorations were discoloured by the dye. Dye penetration was significantly greater in the composite-filled group than in the glass-ionomer group after all forms of cavity preparation ($p<0.05$).

DISCUSSION

Throughout this investigation, care was taken to avoid dehydration of tooth samples. For each of the groupings established, specimens were used with carious lesions of approximately the same size and localization. These measures were instituted as such factors significantly affect the results of bonding studies (42). Despite these precautions, fairly large standard deviations were seen throughout this study, doubtless related to inter-tooth differences with regard to origin, age, storage duration and caries pathology.

Complete removal of carious tooth substance was not achieved in this study using the nanosecond-pulsed Nd-YAG laser. Other authors have achieved varying levels of caries removal using Nd-YAG laser devices emitting longer pulses of radiation at 1064 nm. Myers et al reported effective ablation of incipient pit and fissure lesions in extracted human teeth (43), but Parkins et al (44) described use of a conventional dental handpiece to complete laser cavity preparation in carious enamel and dentin of primary molars. In a 3-year clinical trial, White et al (3) used Nd-YAG laser irradiation for caries removal, but full cavity preparation was often completed using conventional methods as an adjunct. Irradiation at 1064 nm is not strongly absorbed and consequently penetrates relatively well through enamel and dentin (3). Therefore, even in the absence of visible damage from irradiation to hard tissue structures, an adequate thickness of hard tooth substance is essential to provide pulpal shielding. A residual dentin thickness of 2 mm has been advocated to ensure pulpal protection (3). Effective ablation with minimal detrimental side-effects may be achieved by the use of ultrashort pulses in the pico- or femtosecond range. Efficient ablation of almost all tissue types should be possible at these parameters due to the ability of ultrashort pulses to interact with matter regardless of specific linear absorption characteristics (23, 45).

In this investigation, nanosecond-duration pulses of laser irradiation at 1064 nm at appropriate parameters caused minimal structural changes or damage in underlying dentin. Irradiated hard tissue surfaces showed almost a complete absence of thermal or mechanical damage in the form of cracks, craters or melting. Two factors which probably contribute to this phenomenon are the strong damping by the organic tooth matrix of acoustic waves, as well as the very short duration of the stress impulse. Similar results were obtained by Kimura et al (22, 26, 46) using the nanosecond-pulsed Nd-YAG laser, and by Niemz (45) using a picosecond Nd-YLF laser.

Caries removal using the laser was incomplete. Although Ehudin et al (47) reported the possibility of bonding resins to the collagenous structures in carious dentin, an adequate bond between the resin or the glass ionomer and the residually carious tooth surface was not achieved in this investigation. These results are in agreement with resin bond-strength measurements performed on healthy hyper- and demineralized dentin samples by Perdigao et al (48), where bond strengths were greatest with healthy dentin and weakest with demineralized dentin. Areas of hypermineralization and demineralization are found below or within carious lesions, respectively (48).

Glass-ionomer restorations were occasionally discoloured by the methylene blue dye, even in the absence of leakage at the tooth–restoration interface. This resulted from penetration of the dye into the restorative material, which appeared microscopically less homogeneous than the composite resin. Although some microleakage occurred with both materials, composite restorations recorded more specimens with deeper dye penetration than did the glass-ionomer restorations, suggesting that the dentinal tubules were better sealed at the tooth–restoration interface by the glass ionomer product. This is in agreement with the findings of Kaplan et al (49), who observed less microleakage in non-retentive cavities using glass ionomer cement than composite resin. Glass ionomer materials bond chemically to tooth substance, whereas composite resins rely on physical microretention through interdigitation with surface irregularities, without the establishment of a chemical bond.

No difference with regard to microleakage was observed between drill-prepared samples and specimens prepared by drilling followed by irradiation. This observation is doubtless related to an almost complete absence of laser-induced morphological changes in the present samples. Chemical changes have been reported in Nd-YAG laser-irradiated dentin, which might be expected to affect the tooth–restoration interface (51). However, those studies were performed at far greater energy densities using longer-pulsed irradiation than in the present investigation. White et al (50) also identified a physical modification threshold by longer-pulsed Nd-YAG irradiation for dentin which was significantly greater than the maximum $8\,\mathrm{J\,cm^{-2}}$ used in the present investigation. Higher fluences were not used in this investigation because they caused manifestations of excessive thermal effects; smell of burning, charring and desiccation. Libermann et al (32) reported that finishing drill-prepared cavity walls with a defocused Nd-YAG laser beam increased marginal microleakage in extracted human teeth restored with glass ionomer cement.

The complex nature of the tooth–restoration interface is illustrated in a study by Melendez et al (52), in which significantly decreased bond strengths were determined using Ketac glass ionomer cements after CO_2 laser irradiation, but significantly elevated bond strengths resulted using Fuji glass ionomer cement. The significance of cement composition, cement delivery systems, and tooth-related factors remains unresolved, and illustrates well the need for further research into this topic.

Several investigators have reported enhanced dentinal bonding with composite materials after laser pre-treatment using the CO_2 laser; these effects are primarily attributed to changes in dentin surface morphology which enhance micro-interdigitation and retention (36, 40). However, routine clinical use of the CO_2 laser would require precise control of irradiation procedures to ensure a homogeneous effect whilst avoiding the sequellae of excessive heat generation. Very few investigations into the effects of laser irradiation on composite resin bonding have been performed at a wavelength of 1064 nm. Roberts-Harry et al (53) reported longer procedure durations, more discomfort and less reliable bond strengths using the Nd-YAG laser for etching of teeth prior to orthodontic bracket placement, as an alternative to conventional acid-etch techniques. However, it should be noted that in those investigations, laser irradiation was used as an alternative to acid-etch techniques, whereas in the present investigation, irradiation served as an adjunct to conventional treatment. The interaction between dental hard tissue and restorative materials is influenced by multiple factors; type of interaction, tooth-surface morphology and tooth-surface composition. The two latter entities can be affected by the laser configuration as an entity, comprising wavelength, fluence, total energy density, pulse duration, repetition rate and duty cycle. Thus, further investigations are required to study the effects of various laser parameters on subsequent bonding behaviour in enamel and dentin. Moreover, the influence of stresses such as thermocycling on the established interface should be documented before clinical application of these techniques is attempted. Several investigations on these topics are currently in progress.

The results of the present study demonstrate that thermal and morphological laser effects, as well as their influence on bonding mechanisms, must be fully investigated before clinical application of laser technology as an alternative to the dental drill is viable.

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