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THE EFFECT ON THE ULTRASTRUCTURE OF DENTAL ENAMEL OF EXCIMER-DYE, ARGON-ION AND CO_2 LASERS

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Abstract

This study aimed to investigate the ultrastructural changes that occur in dental enamel irradiated with pulsed excimer-dye, continuous-wave (CW) argon-ion and CW CO_2 lasers. The pulsed excimer-dye laser produced deep craters, rough damaged surfaces with underlying porosity and amorphous vitrified material. The vitrification of the enamel indicated that the temperature in these areas must have been at least in the range 1280 to 1600°C. The CW argon-ion laser irradiation produced a changed non-cratered surface with inter-crystalline porosity and a mixture of small and some large irregularly packed recrystallized enamel crystals. The CW CO_2 laser produced shallow craters, surface crazing and lifting off and removal of the surface layer to expose the underlying roughened enamel. The ultrastructure revealed inter- and intra-crystalline porosity, a mixture of small but variable size irregularly packed recrystallized enamel crystals and also well packed large crystals which indicated further grain growth. The porosity in lased enamel was overall very similar to that seen in enamel heated in an electric furnace to a temperature of 600°C. The presence of recrystallized enamel crystals indicated a temperature rise of ~1000°C and the grain growth indicated that a temperature $\geq$ 1000°C existed for some time after the laser irradiation. In general the excimer-dye laser produced most surface destruction because of its higher power density and shorter interaction time and the argon-ion laser produced least damage. These results indicated that the lasers used in this study require much more refinement before they can find therapeutic application to dental enamel, and this may well be the case for other lasers being investigated for clinical dental practise.

Key Words: Laser irradiation, dental enamel, scanning electron microscopy, transmission electron microscopy, ultrastructure, recrystallization.

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Introduction

In recent years there has been renewed interest in the application of present day laser technology to clinical dental practice (Melcer, et al 1984; Kimura, et al 1983; Myers and Myers 1985; Myers, et al 1985). Using a fibre optic system of delivery into the mouth laser irradiation has been used to date for the removal of soft caries, the etching of enamel surfaces and the incision and excision of oral soft tissues. Other proposed applications of lasers to dentistry which have shown promise have been in the area of dental appliances (Smith et al 1972; Brune 1980; Gordon and Smith 1970a,b; Preston and Reisbeck 1975) the preparation of teeth for restorative material (Stewart et al 1985; Nammour et al 1987; Hibst and Keller 1989; Keller and Hibst 1989; Paghdiwala 1991) and the improvement of the tooth's surface to prevent caries lesion formation (Stern 1969; Stern, et al 1972; Yamamoto and Ooya 1974; Yamamoto and Sato 1980a,b; Nelson, et al 1986a,b, 1987; Oho and Morioka 1990). A possibly useful but little understood finding has been the anaesthetizing effect of laser irradiation on dentine as reported by the manufactures of the American dental laser in their pamphlet (1990).

The pulsed or continuous-wave (CW) CO_2 lasers have wavelengths in the infrared region of the electromagnetic spectrum (~10.6μm) and are generally regarded as being more efficient in interacting with enamel since dental enamel has intense absorption bands in the infrared region (Nelson and Williamson 1982; Duplain et al 1987). Featherstone and Nelson (1987) showed that specific wavelengths of 9.32μm and 10.59μm in the infrared region were more efficient than other wavelengths in interacting with enamel. Brune (1980) used a pulsed CO_2 laser with energy densities of 10 or 100 or 200Jcm^{-2} to prepare cavities or pin holes for retention and concluded that the laser may be a potential replacement for the dental drill in cases needing small cavities. Similarly Boehm, et al (1977) concluded that lasers may greatly facilitate the application of a durable pit and fissure sealant. Another main area of study has been the investigation of the inhibitory effects of laser irradiation on caries lesion formation (Stern 1969;

Stern, et al 1972; Yamamoto and Ooya 1974; Yamamoto and Sato 1980a,b; Nelson, et al 1986a,b, 1987; Oho and Morioka 1990).

Nelson, et al (1986b) using a pulsed CO_2 laser showed that an energy density of 50Jcm^{-2} inhibited artificial caries lesion formation to a greater extent than 10Jcm^{-2}. However they suggested that the low energy density (<50Jcm^{-2}) pulsed laser irradiation was more clinically suitable because there was less chance of damaging oral soft tissue. Nelson, et al (1986a,b) further suggested that the inhibitory effect of caries lesion formation was wavelength dependent, 9.32μm being found to be the most effective. According to them pulsed lasers were better than CW lasers because the pulsed lasers provided a way for increasing the peak power density while keeping the pulse energy density constant. They concluded that by using high power densities and short interaction times the fusion melting and recrystallization of the enamel crystallites was confined to the surface region without affecting the underlying enamel or more importantly the underlying dentine or pulp. Yamamoto and Sato (1980a) also showed the potential of the Nd:YAG laser, which has a wavelength 1.06μm, to fuse the dental enamel and to make it highly resistant to subsequent dissolution. However, to enhance the laser interaction with the enamel, Yamamoto and Sato (1980a), Kimura et al (1983) and more recently Tagomori and Morioka (1989) and Oho and Morioka (1990) painted absorption materials on the irradiated enamel surface enabling more efficient absorption of the laser's energy. Why lased enamel is more resistant to artificial caries formation is still unclear. It is possible that different mechanisms may operate with different types of lasers, their wavelengths and the particular conditions under which irradiation occurs. Many clinicians have enthusastically embraced laser technology, but from the published literature there still appears to be little understanding of what laser irradiation is doing to hard tissues. Until such knowledge is obtained the full potential of laser technology cannot be achieved nor its limitations assessed.

This paper concerns itself with assessing the ultrastructural changes produced in dental enamel by using three different types of lasers, namely a pulsed excimer-dye laser, a CW argon-ion laser and a CW CO_2 laser. Some results of a CW CO_2-laser were reported in an earlier paper (Ferreira et al 1989) and further results are now represented together with the data from the other two lasers for comparison. These lasers were chosen because of their considerably different wavelengths and power densities.

Material and Methods

60 caries-free human premolar and molar teeth extracted for orthodontic reasons and obtained from the Royal Dental Hospital of Melbourne were collected and stored in distilled water to which a few crystals of thymol were added to control infection. Lapped and polished hard ground sections were made from these teeth and the enamel surfaces,

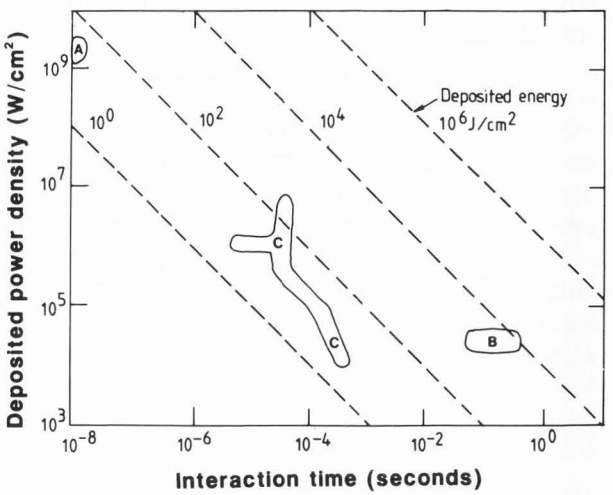


Fig. 1. Diagrammatic representation of deposited power density and interaction time for pulsed excimer-dye laser (A), CW argon-ion laser (B) and CW CO_2 laser (C).

both natural and sectioned, 15 teeth were irradiated using a pulsed excimer-dye laser (Luminics series TE-860-3 model TE861M-3 laser), 15 teeth with a continuous-wave (CW) argon-ion laser (Coherent Inovar 60/70 series ion laser) and 30 teeth with a CW CO_2 laser (Model Cohered Everlase 535) using power densities and interaction times shown in Fig. 1.

CW CO_2 laser irradiation with a wavelength of 10.6μm, power density ranging from 10^4-10^6Wcm^{-2} and an interaction time ranging from 6-520μs was used (Fig. 1). This gave an energy density ranging from ~10-200Jcm^{-2} and covered the range (10 to 50 Jcm^{-2} recommended by Nelson et al (1986a,b) for clinical application. The wavelengths used for the excimer-dye laser were 382.8 and 489.9nm. The operating power density of ~10^9Wcm^{-2} and pulse interaction times of 10ns were selected to give an energy density similar to the CW CO_2 laser (Fig. 1). For the CW argon-ion laser the all line mode of irradiation consisting of wavelengths 561.7, 514.2, 496.5, 488.0, 476.5, 475.9, 472.7 and 465.8nm was used. However, when the CW argon-ion laser was operated at energy densities similar to those used for the CW CO_2 laser or the pulsed excimer-dye laser no visible surface interaction with the enamel was noticed. Consequently the laser power density of ~2×10^4Wcm^{-2} and interaction time of ~0.1s were selected as they produced some surface interaction with the enamel. These operating conditions for the CW argon-ion laser resulted in a much higher energy density (~2×10^3Jcm^{-2}) than for the pulsed excimer-dye (~30Jcm^{-2}) and the CW CO_2 (~10-200Jcm^{-2}) lasers.

For laser irradiation using the excimer-dye or the argon-ion laser the sample was attached to a traversing mechanical stage and exposed to the laser beam which was focused onto the sample by a lens and single or multiple traverses made across the enamel surface. The tracks were

made to slightly overlap to produce a large lased area. For the excimer-dye laser which gives a pulsed irradiation of 30-50 pulses per second the rate of traverse was calculated and adjusted so that only a slight overlap occurred between pulses to form a continuous lased track. For the CW CO_2 laser irradiation the beam was focused onto the sample by a lens. The tooth samples were attached to the outer edge of a wheel which could be rotated at various selected speeds, to give a shorter interaction time. The sample was simultaneously translated to give lased areas with a minimal overlapping. The mean irradiation time for the CO_2 laser was calculated knowing the diameter of the rotating wheel and its speed of rotation. The power density for the laser irradiation was calculated from the values of power used and the beam diameter of the focussed spot on the specimen. The spot diameter was determined on the sample using a microscope with a graticule eye piece calibrated in divisions of 10μm and depth determined by through focusing on the sample. Laser irradiated samples were initially examined by reflected light microscopy to select the most suitable lased area for investigation by scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

For SEM the sections were first coated with a conducting layer of platinum and then examined with a Hitachi S/570 SEM operating in secondary electron mode using accelerating voltages of 5,10,20 or 30 kV. For TEM ultra-thin sections were prepared by the selected-area argon-ion beam thinning technique (Phakey et al, 1974; Palamara et al, 1980). This method involved enclosing the selected area of the laser irradiated area by cementing a slotted grid onto the section. The mounted specimen was then thinned in an argon-ion-beam thinner until perforated in the area to be examined (Fig. 2a). The perimeter of the hole was mapped out into lettered areas using a light microscope as described previously (Orams et al 1980, Palamara et al 1986). This enabled a direct correlation between a particular laser irradiated region as observed in the light microscope (Fig. 2b) and its ultrastructure as examined by TEM and/or SEM. In some cases the ultrathin sections were first studied by TEM and then were re-examined by SEM to correlate light microscope, scanning electron microscope and transmission electron microscope observations made on a particular preselected area of the sample.

Selected area electron diffraction was used for the identification of crystal structure. The d-values of the polycrystalline ring pattern were calculated and compared with the d-values of the calcium phosphate structures given in the Diffraction Data (1980). For single-crystal spot patterns, the distance and angles between different diffraction spots, directly measured on photographic film, were indexed and identified by means of a computer program. This computer program used the stored crystallographic data of the known calcium phosphate phases and generated electron diffraction patterns for direct comparison with the observed diffraction pattern.

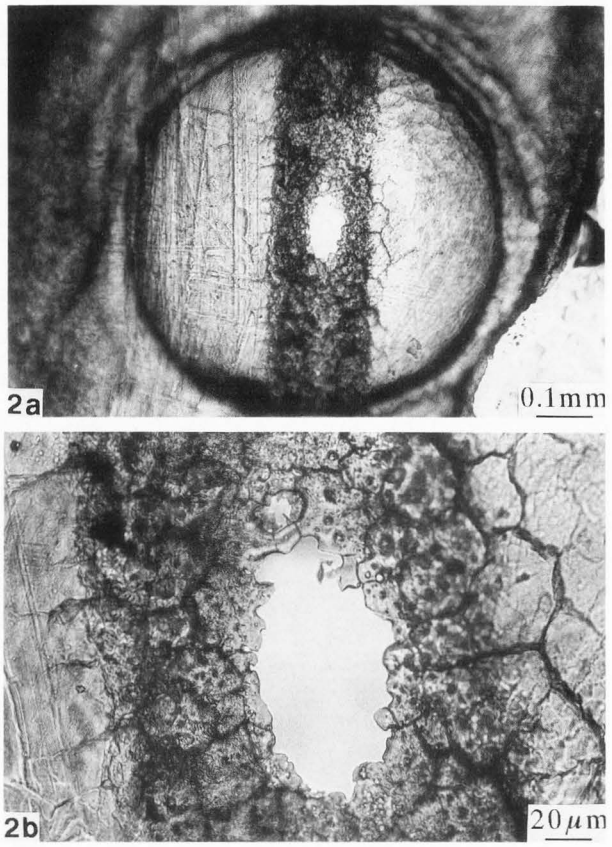


Fig. 2. Light micrograph of CW CO_2 lased enamel surface. (a) Showing a sample mounted on a circular grid and thinned in an argon-ion beam thinner. (b) Higher magnification of perforated area in (a) which was mapped out into lettered areas to allow direct correlation in the transmission or scanning electron microscope.

Results

Pulsed excimer-dye laser:

When a fixed area of a thick sectioned tooth enamel surface was irradiated with 5 pulses from an excimer-dye laser without traversing the specimen a shallow crater approximately 120μm in diameter was produced in the sample by the focused beam (Fig. 3). With continued irradiation the crater became deeper until complete perforation of the specimen occurred. Occasionally some of the material ablated from deep within the crater was found to be deposited around the periphery of the crater and on the non-irradiated surface.

Fig. 4a shows a set of parallel continuous channels, produced by making successive runs across the polished enamel surface, using a pulsed excimer-dye laser. Each channel was approximately 50 to 100μm wide with a depth of approximately half of its width. Between each channel were strips of non-irradiated smooth polished enamel surface. The walls and floor of each channel showed a rough texture composed of projecting mound-like structures sur-

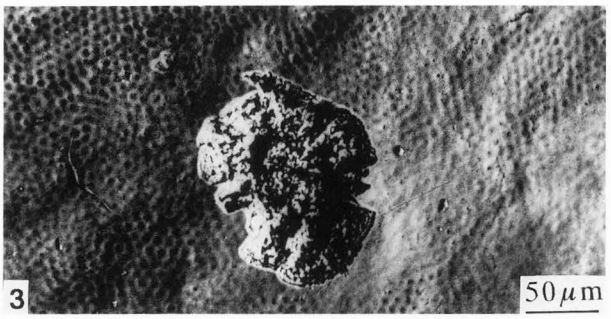


Fig. 3. Scanning electron micrograph of excimer-dye lased enamel tooth's surface showing an irregular shaped crater with roughened floor after exposure to five pulses.

rounded by pits and crevasses (Fig. 4a,b). The mound-like structures were of the order of size 5 to 10μm in diameter. At higher magnification the surface of the mound-like structures appeared to be composed of smaller particulate matter of approximately size 0.5 to 1.0μm in diameter.

Large lased surface areas, produced by successive parallel overlapping channels, when examined by TEM showed extensive damage observed as rounded irregular masses of crystals, loss of crystal form and amorphous material identified by the diffuse nature of the selected-area electron diffraction patterns (Fig. 5).

The surface layer of damaged crystals was removed by argon-ion beam thinning as it produced minimal artifactial changes (Phakey et al.1974; Palamara et al.1980). The examination of the underlying areas of lased enamel by TEM revealed further localized damage in the form of circular and irregular holes (approximately 0.1μm or more in diameter) surrounded by a zone of material with a diffuse 'bubble-like' appearance (Fig. 6). Selected area electron diffraction showed that this bubble-like material was amorphous. The bubble-like material was probably vitrified enamel and its distribution in the sample was uneven (Fig. 7). In some samples the vitrified enamel filled interprismatic and intercrystalline spaces (Fig. 7,8). Further away from the holes the crystal morphology, orientation and packing were unchanged from that of non-irradiated enamel.

CW argon-ion laser:

Single runs of irradiation with this laser produced tracks approximately 100μm in width. Large lased areas produced by successive parallel and slightly overlapping tracks when examined by SEM showed a surface which was changed by the laser irradiation but was relatively smooth in appearance compared to the rough textured channels produced by the excimer-dye laser (Fig. 9a). It was only at high magnification that the real extent of the damage was apparent because this surface was seen to be damaged by multiple microscopic pits and cracks, although large craters were not observed (Fig. 9b). When the lased areas were examined by TEM, they showed mainly inter-crystalline and some intra-crystalline porosity and a mixture of small and

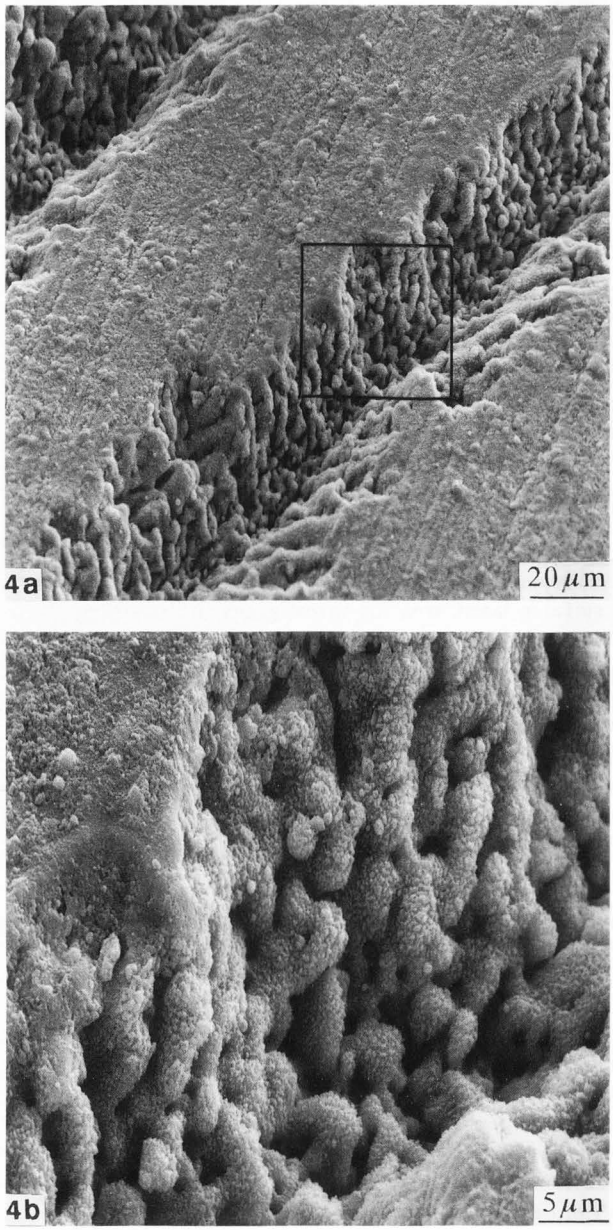
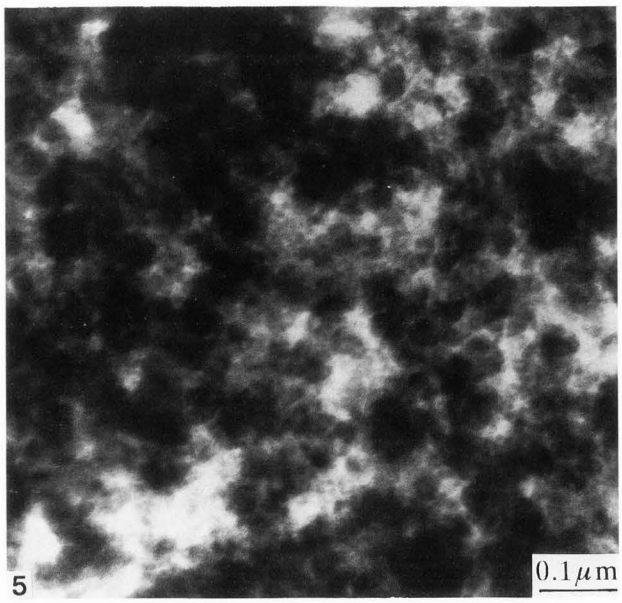
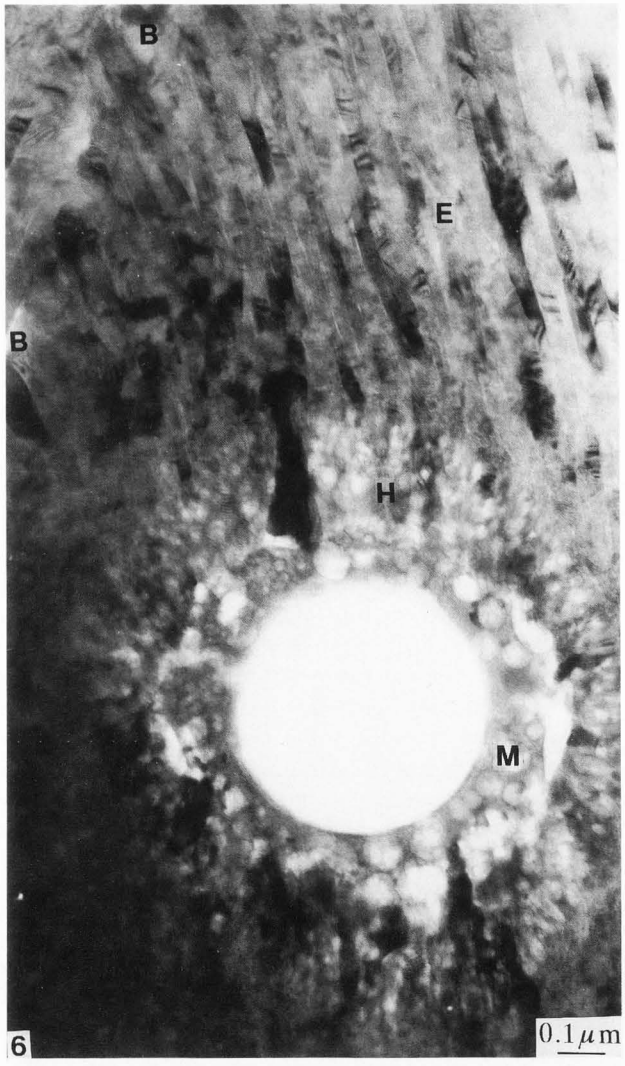


Fig. 4. Scanning electron micrographs of longitudinal section of enamel lased with an excimer-dye laser. (a) Showing parallel laser channels on the surface obtained by traversing the sample during irradiation. (b) Higher magnification of area enclosed in the square in (a) showing pitted and mound-like structures in the lased area.

some irregularly shaped large crystals, with a different morphology from typical non-irradiated enamel crystals, having all the characteristic features of recrystallization. These recrystallized crystals varied in width from approximately that of normal enamel crystals ($\sim$ 50 to 70nm) to one order of magnitude greater in size (Figs. 10,11). Electron diffraction identified all of these crystals as apatite.





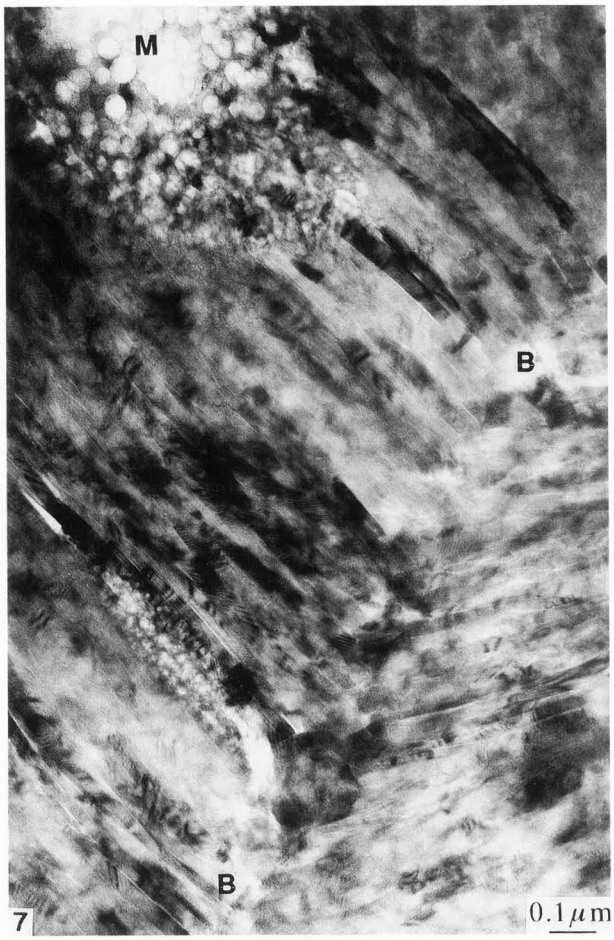


Fig. 5. Transmission electron micrograph of excimer-dye lased enamel surface showing extensively damaged surface layer with little crystalline structure remaining.

Fig. 6. Transmission electron micrograph of excimer-dye lased enamel from underneath damaged surface layer (similar to that shown in Fig. 5) after removal of this layer. Heat effected (H) and vitrified enamel (M) is seen around the perforation produced by the irradiation. Unaffected enamel (E) and a prism boundary (BB) are present further peripherally.

Fig, 7. Transmission electron micrograph of a excimer-dye lased enamel region similar to that in Fig. 6. showing uneven distribution of heat affected and vitrified enamel (M). Note some vitrified material filling intercrystalline spaces near the bottom left of the field of view close to the prism boundary (BB).

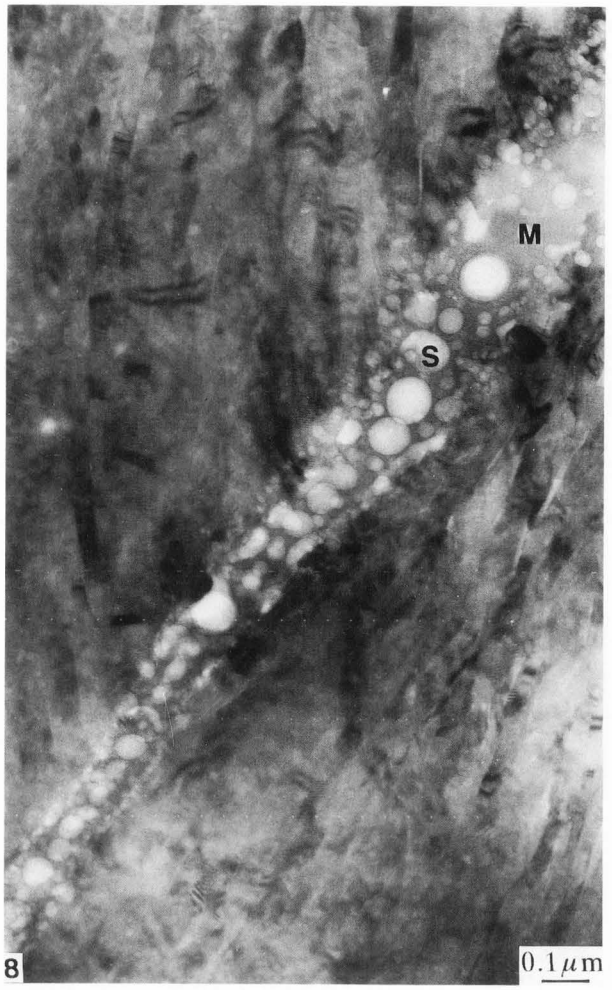


Fig. 8. Transmission electron micrograph of excimer-dye lased enamel showing vitrified material (M) filling an interprismatic space along the prism boundary. Note the bubble-like structures (S) in the vitrified enamel.

CW CO_2 laser:

SEM of enamel surfaces irradiated by single runs of the CW CO_2 laser revealed extensive crazing and cratering of the enamel surface. Rough exposed enamel regions, due to the lifting off and removal of the layer of crazed and cratered enamel, were also commonly observed but were partly dependent on the energy density used and on the underlying prism orientation (Fig. 12). TEM of the crazed and cratered enamel regions showed that in some areas the ultrastructure was similar to that observed in the argon-ion lased enamel (Fig. 13). For example inter- and intra-crystalline porosity, a mixture of small and numerous irregularly shaped large recrystallized enamel crystals were present (Fig. 13). However, unlike the argon-ion lased enamel there were present well packed large grains some of which enclosed smaller subgrains (Fig. 14a) while the others were of a more crystallographic shape (Fig. 14b).

These features were indicative of grain growth after recrystallization. The ultrastructure of the rough exposed enamel formed from the lifting off and removal of the top layer of crazed or cratered enamel showed crystals of size and shape similar to those of unlased enamel but some inter- and intra-crystalline voids were present as has been reported previously (Ferreira et al 1989)

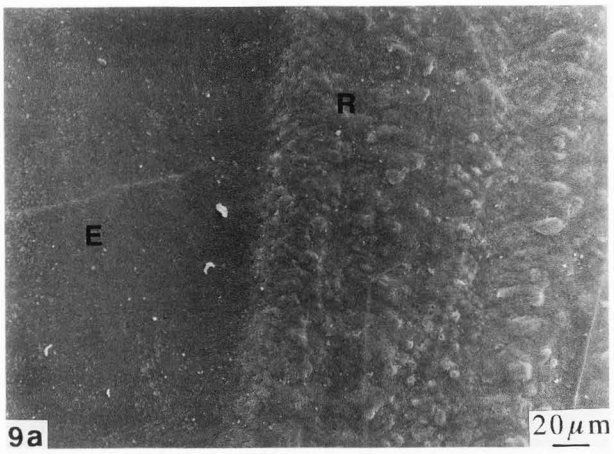
The ultrastructural changes described above for the three lasers reported here were constant over the large lased areas and there was no observable difference due to the minimal overlapping of the laser runs.

Discussion

The structural change produced in enamel by the lasers used in this investigation were essentially similar in nature but varied markedly in degree. It was evident that under the conditions of operation the pulsed excimer-dye laser produced greater structural damage and the CW argon-ion laser less structural damage than that produced by the CW CO_2 laser.

The pulsed excimer-dye laser extensively damaged the enamel surface; the damage ranging from roughening of the surface to complete destruction of the enamel crystals whilst under the damaged surface were localized pockets of amorphous bubble-like material indicating vitrification of enamel. The vitrified enamel was more likely due to a rapid quenching of the melted material rather than to the formation of laser induced mechanical shock waves as has been suggested by Vahl (1969). The vitrification of enamel indicated that the temperature in these areas must have been at least in the range 1280 to 1600°C because tooth enamel melts above 1280°C (Corcia and Moody 1974) and hydroxyapatite changes phase and melts at about 1600°C (Kuroda and Fowler 1984). The vitrified enamel material was found to flow into intercrystalline voids and in prism boundaries present in enamel. Commonly present between the vitrified enamel and the surrounding normal enamel was a layer of heat affected enamel. The presence of vitrified and heat affected enamel layers may decrease the permeability of the irradiated surface and make it resistant to dissolution. The craters in the enamel and the ablated material deposited onto the enamel surface surrounding the craters indicated vaporization of enamel at temperatures in excess of its melting point. The vaporization and ablation of good enamel from the tooth's surface and the temperature reached can not justify the use of the excimer-dye laser as a clinical treatment of healthy enamel to decrease its permeability but perhaps it could be better adapted to the preparation of cavities.

The poorly packed crystals and numerous inter- and intra-crystalline voids present in both CW argon-ion lased and CW CO_2 lased enamel were very similar to those found in enamel heated in a furnace to a temperature of 600°C (Palamara et al 1987). This porosity was probably due to the carbonization of organic material, loss of carbonate



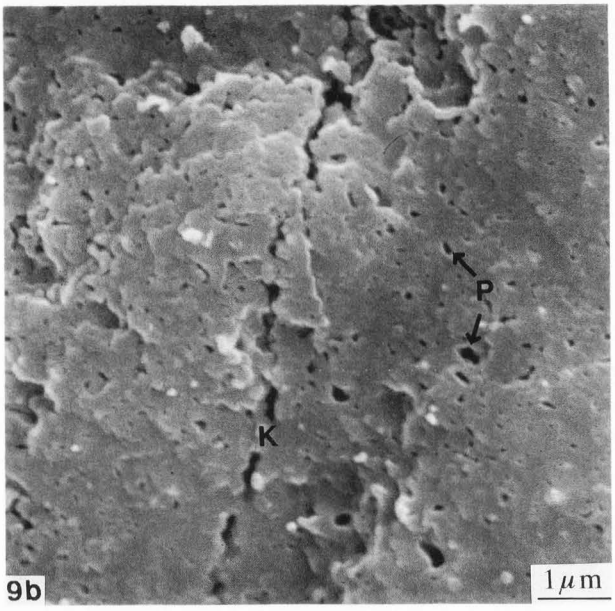


Fig. 9. Scanning electron micrographs of enamel surface irradiated with a CW argon-ion laser. (a) Showing non-irradiated enamel (E) and slightly roughened enamel (R) resulting from irradiation. (b) Higher magnification of the region around R in (a) showing pitting (P) and cracking (K) of the irradiated surface.

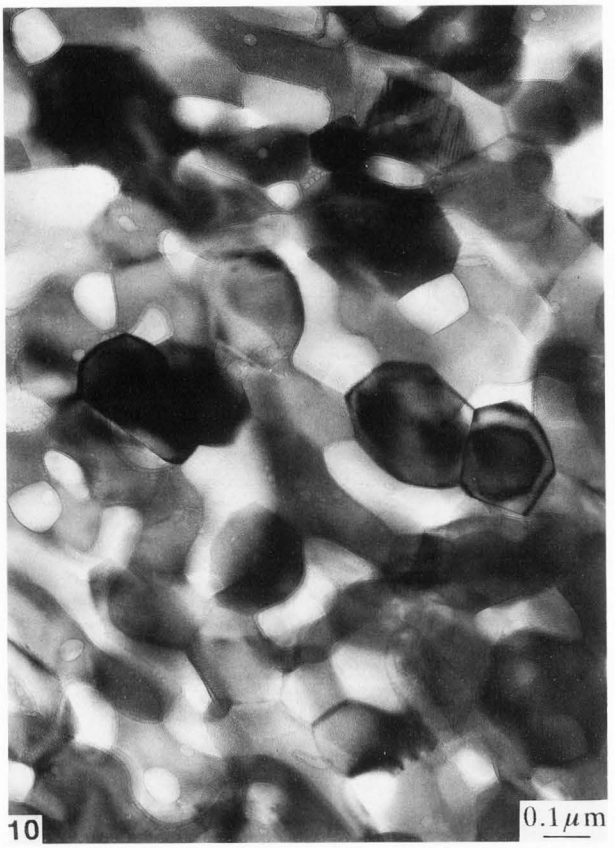


Fig. 10. Transmission electron micrograph of CW argon-ion lased enamel showing recrystallized crystals which have replaced the typical crystals of normal enamel. Note the inter-crystalline and some intra-crystalline porosity.

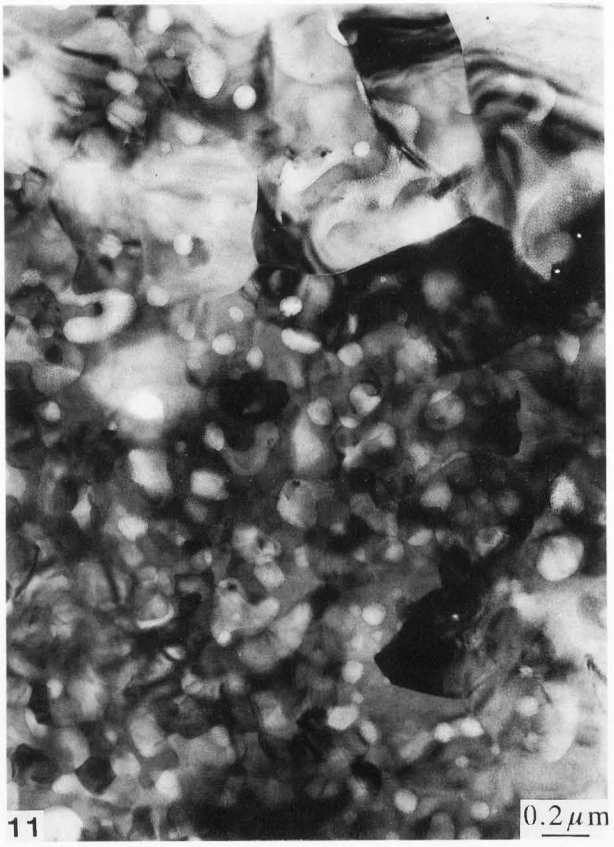


Fig. 11. Transmission electron micrograph of enamel lased with CW argon-ion laser, showing well packed large recrystallized grains in the region on the top right of the field of view and poorly packed small recrystallized crystals on the bottom left of the field of view. Also note inter-crystalline porosity.

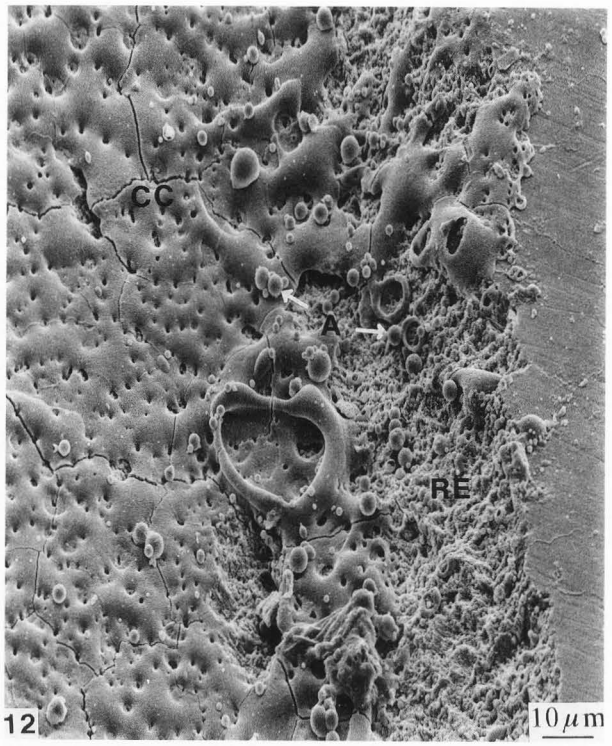


Fig. 12. Scanning electron micrograph of a CW CO_2 lased enamel surface showing crazed and cratered (CC) enamel and rough exposed (RE) enamel and the ablated material (A) deposited on the surface.

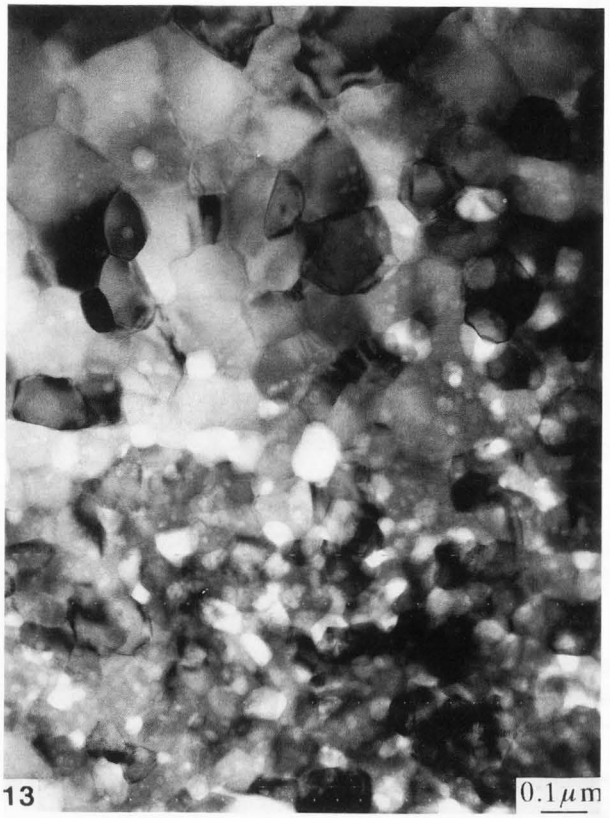


Fig. 13. Transmission electron micrograph of enamel lased with a CW CO_2 laser showing a region of well packed large recrystallized grains on the top left of the field of view and poorly packed small recrystallized crystals on the bottom of the field of view. Note the similarity with argon-ion lased enamel (Fig. 11).

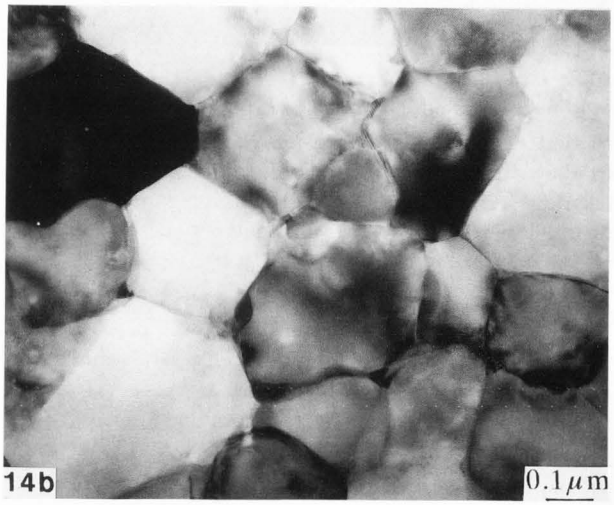


Fig. 14. Transmission electron micrographs of enamel irradiated with a CW CO_2 laser. (a) Showing well packed large grains containing small subgrains (arrowed) with poorly defined boundaries. (b) Showing homogeneous crystallographically shaped large grains.

and dehydration of the enamel. The porosity would also cause the poor packing of the crystals. Poorly packed small recrystallized crystals and well packed large recrystallized crystals were present in both CW argon-ion lased and CW CO_2 lased enamel but not in the excimer-dye lased enamel.

Consistent with previous results (Ferreira et al 1989) the CW CO_2 laser produced extensive crazing, cratering and caused rough exposed enamel surfaces resulting from the lifting off of the lased surface layers. Large recrystallized enamel crystals similar to those seen in the argon-ion laser irradiated enamel samples were present but in greater numbers. It is known that the recrystallization temperature for metals and alloys varies from 0.3 to 0.7 of the absolute melting temperature (Callister 1991). The variation depends upon several factors including the amount of prior cold work and the purity of the metal or alloy. For a ceramic type material such as dental enamel the recrystallization temperature would lie at the higher end of the range namely 0.7 of the absolute melting point for enamel. Hence the temperature reached in enamel where recrystallization was observed would be approximately 1000°C. This is consistent with temperature measurements made by Featherstone and Nelson (1987) who showed that the temperature of the surface melt region when irradiated with a pulsed CO_2 laser ranged from 800-1100°C. In the absence of cold work in enamel crystals, the recrystallization can result from the surface poisoning of the grains by impurities, organic material and CO_2 released from non stoichiometric hydroxyapatite. Moreover the vapour and the gases released at high temperatures may exert extreme pressures at elevated temperatures causing deformation in the original enamel crystals. Such deformation would promote recrystallization. Furthermore, if a metal or a ceramic specimen is left at an elevated temperature then grain growth occurs by the migration of grain boundaries; some grains grow at the expense of others that shrink (Callister 1991). The large grains, indicating grain growth, characteristically found in CW CO_2 lased enamel further suggested that temperatures $\geq$1000°C existed for some time after the laser irradiation. Some grain growth may also have occurred in CW argon-ion lased enamel. Although no grain growth or recrystallization was observed for the pulsed excimer-dye laser, the vitrification of the enamel suggested that the temperature in these areas must have at least reached the melting point for enamel. However, in the vaporized regions the temperature could have well exceeded that for the melting point of enamel.

To obtain a surface interaction with the enamel the argon-ion laser was operated at a higher energy density ($\sim 2\times10^3 Jcm^{-2}$) compared to the pulsed excimer-dye laser ($\sim 30 Jcm^{-2}$) or the CW CO_2 laser ($\sim$10-200Jcm^{-2}) Obviously it was the power density and the interaction times under which the lasers operated that largely determined the structural changes produced. The surface layer of laser irradiated enamel has been previously described as having a fused and/or glazed appearance (Stern et al 1972; Nelson et al 1987; Tagomori and Morioka 1989). However, the observation of CW argon-ion and CW CO_2 laser irradiated enamel reported here showed that the changes in the surface layer were likely due to the recrystallization and grain growth of new or preexisting crystals although the possibility of sintering of the original enamel crystals could not be ruled out.

Acknowledgements

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References

American dental laser pamphlet: (1990). The revolutionary American dental laser. Suite 216, 280 North Woodward Avenue, Birmingham, Michigan 48009 USA.

Boehm R, Baechler T, Webster J, Janke S. (1977). Laser processes in preventive dentistry. Optical Eng. 16:493-496.

Brune D. (1980). Interaction of pulsed carbon dioxide laser beams with teeth in vitro. Scand, J.Dent.Res. 88:301-305.

Callister WD Jr. (1991). In: Material Science and Engineering. Second edition, John Wiley and Son Inc. Brisbane, Australia. pp 178-183.

Corcia JT, Moody WE (1974). Thermal analysis of human dental enamel. J Dent Res. 53:571-580.

Diffraction date file for inorganic minerals (JCPDS). (1980). International center of diffraction data. Swarthmore, Pa, USA.

Duplain G. Boulay R, Balanger P A. (1987). Complex index of refraction of dental enamel at CO_2 laser wavelengths. App Optics. 26:4447-4451.

Featherstone JDB, Nelson DGA. (1987). Laser effects on dental hard tissues. Adv Dent Res. 1:21-26.

Ferreira JM, Palamara J, Phakey PP, Rachinger WA, Orams HJ. (1989). Effects of continuous-wave CO_2 laser on the ultrastructure of human dental enamel. Arch Oral Biol. 34:551-562.

Gordon TE, Smith DL. (1970a). Laser in the dental lab. Laser Focus. 6:37-39.

Gordon TE, Smith DL. (1970b). Laser welding of prothesis an initial report. J Post Dent. 24:472-476.

Hibst R, Keller U. (1989) Experimental studies of the application of the Er:YAG laser on dental hard substances: I. Measurement of ablation rate. Laser's Surg Med 9:338-344.

Keller U, Hibst R. (1989) Experimental studies of the application of the Er:YAG laser on dental hard substances: II. Light microscopic and SEM investigations. Laser's Surg Med 9:345-351.

Kimura H, Sohmura T, Tsutsumi N, Okazaki M. (1983). Applications of Laser on dental treatment. J.Osaka Univ Dent Sch. 23:31-42.

Kuroda S, Fowler BO. (1984). Compositional, structural, and phase changes in vitro laser-irradiated human tooth enamel. Calcif Tissue Int. 36:361-369.

Melcer J, Chaumette MT, Melcer F, Dejardin J, Hasson R, Merard R, Pinaudeau Y, Weill R. (1984). Treatment of Dental Decay by CO_2 Laser Beam: Preliminary Results. Laser Surg Med. 4:311-321.

Myers TD, Myers,W.D. (1985). Use of a laser for debridement of incipient caries. J Prosthet Dent. 53:776-779.

Myers TD, Myers WD, Stone AM. (1985). In vitro caries removal utilizing the YAG laser. J.Mich Dent Ass. 67:66-67.

Nammour S, Carleer M, Renneboog-Squilbin C, Dourov N. (1987). Use of the laser for welding cracks on dental enamel. J Biol Buccale. 15:37-43.

Nelson DGA, Jongebloed WL, Featherstone JDB. (1986a). Laser irradiation of human dental enamel and dentine. N.Z.Dent J. 82:74-77.

Nelson DGA, Shariati M, Glena R, Shields CP, Featherstone JDB. (1986b). Effect of pulsed low energy infrared laser irradiation on artificial caries-like lesion formation. Caries Res. 20:289-299.

Nelson DGA, Wefel JS, Jongebloed WL, Featherstone JDB. (1987). Morphology histology and crystallography of human dental enamel treated with pulsed low-energy infrared laser irradiation. Caries Res. 21:411-426.

Nelson DGA, Williamson BE. (1982). Low-temperature laser Raman spectroscopy of synthetic carbonate apatites and dental enamel. Aust J Chem. 35:715-727.

Oho T, Morioka T. (1990). A possible mechanism of acquired acid resistance of human dental enamel by laser irradiation. Caries Res. 24:86-92.

Orams HJ, Phakey PP, Rachinger WA, Zybert JJ. (1980). Ultrastructural changes in the translucent and dark zone of early enamel caries. J Oral Path. 9:54-61.

Paghdiwala AF. (1991). Does the laser work on hard dental tissue? J Amer Dent Assoc. 122:79-80.

Palamara J, Phakey PP, Rachinger WA, Orams HJ. (1987). The ultrastructure of human dental enamel heat treated in the temperature range 200^{0}C to 600^{0}C. J Dent Res. 66:1742-1747.

Palamara J, Phakey PP, Rachinger WA, Orams HJ. (1986). Laminated zones in human enamel caries. J Oral Path. 15:109-114.

Palamara J, Phakey PP, Rachinger WA, Orams HJ. (1986). The ultrastructure of the intact surface zone of white spot carious lesions in human enamel. Oral Pathol. 15:28-35.

Palamara J, Phakey PP, Rachinger WA, Orams HJ. (1980). The electron microscopy of surface enamel of human unerupted and erupted teeth. Arch Oral Biol. 25:715-725.

Phakey PP, Rachinger WA, Orams HJ, Carmichael GC. (1974). Preparation of thin sections of selected areas. In: Electron Microscopy (Edited by Sanders JV, Goodchild DJ). Vol 1 pp 412-413. Austraian Academy of Science, Canberra.

Preston JD, Reisbick MH. (1975). Laser fusion of selected dental alloys. J Dent Res. 54:232-258.

Smith DL, Burnell AP, Gordon TE. (1972). Laser welding of gold alloys. J Dent Res. 51:161-167.

Stewart L, Powell GL, Wright S. (1985). Hydroxyapatite attached by laser: A potential sealant for pits and fissures. Operative Dent. 10:2-5.

Stern RH. (1969). The potential of various lasers in caries prevention. Ann NY Acad Sci. 168:642-648.

Stern RH, Vahl J, Sognnaes RF. (1972). Lased enamel: Ultrastructural observations of pulsed carbon dioxide laser effects. J Dent Res. 51:455-460.

Tagomori S, Morioka T. (1989). Combined effects of laser and fluoride on acid resistance of human dental enamel. Caries Res. 23:225-235.

Yamamoto H, Ooya K. (1974). Potential of Yttrium-garnet laser in caries prevention. J Oral Path. 3:7-15.

Yamamoto H, Sato K. (1980a). Prevention of dental caries by Nd-YAG laser irradiation. J Dent Res. 59:2171-2177.

Yamamoto H, Sato K. (1980b). Prevention of dental caries by acousto-optically Q-switched Nd-YAG laser irradiation. J Dent Res. 59:137.

Vahl J (1969). Applicability of the scanning electron microscope to the topography of the surface of the specimens after laser irradiation. Ann NY Acad Sci. 168:664-680.

Discussion with Reviewers

D Nelson: Were the higher energy densities required for the argon-ion laser due to the relatively low adsorption of this laser light relative to the CW CO_2 laser? If so, did it produce noticable, deeper, subsurface interactions in the enamel?

Authors: Argon-ion adsorption should not be as good as that for the CW CO_2 laser because of the adsorption of the enamel in the 10.6μm region. Hovever penetration depth studies were not made.

D Nelson: Would the amorphous, vitrified material found in enamel lased with the pulsed excimer-dye laser be preferentially disolved by dilute acids relative to sound dental enamel?

Authors: A glassy material with broken bonds should dissolve more than a crystalline material; but no dissolution studies were made on the excimer-dye laser irradiated sample reported here.

SH Ashrafi: You have shown that CW argon ion laser caused less damage to enamel crystals than the other lasers. Do you think that this less damage is not enough not to use CW argon-ion lasers in clinics?

Authors: Although the CW argon-ion laser produces less damage at the tooth surface than the other two lasers examined, it is important to determine the heat transfer to the pulp before the clinical application of the argon-ion laser can be assessed.

D Nelson: Could the excimer-dye laser produce similar crystallographic and morphological observations as the other two lasers if lower densities were used? Conversely if higher power densities were used for the CO_2 and argon-ion laser could similar effects to the excimer-dye laser be produced?
Authors: No such comparisons were made but these exprirments are under consideration.

AF Pagdiwala: The authors state in the abstract and in the discussion that the excimer-dye laser produced most surface destruction due to its higher power density and shorter interaction time. Could other factors also be responsible for the ultrastructural effects, such as differences in tissue absorption of laser energy at different wavelengths?
Authors: Differences in surface appearance using a particular laser (constant wavelength) but different power densities and interaction time suggest these parameters are more important than any other.

AF Pagdiwala: Could it also be that some reactions may be photo-chemical while others are photo-thermal, resulting in different structural changes?
Authors: Such studies can not distinguish between photo-chemical or photo-thermal reactions.