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Effects of Er:YAG Laser on Surface Morphology of Dental Restorative Materials

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Abstract: *The aims of this study were to evaluate the effects of Er:YAG laser on surface morphology of dental restorative materials namely glass ionomer cement, composite resin, polyacid-modified composite resin, resin-modified glass ionomer cement and unfilled resin, and to ascertain the ablation threshold of these materials. Crater diameters, crater depths and crater volumes of the ablated sites were measured to assess the ablation characteristics of different restorative materials. The surface morphology changes varied from nil effect, to ablation, fusion, combustion, and various combinations of these. The ablation threshold of all materials was 40 mJ except Delton (60 mJ).*

Keywords: Er:YAG laser, surface morphology, dental restorative materials, ablation threshold, ablation characteristics

1. INTRODUCTION

Although the invention of the laser by Theodore Maiman[1] dates back to 1960, the first dental laser research only took place in 1964 when Stern and Sognnaes[2] studied the thermal effects of ruby lasers on hard dental tissues. They found that a single pulse of ruby laser between 500 and 2000 J/cm^2 produced fusion and crater in the enamel, whereas the dentine showed charring. In 1965, Goldman et al.[3] reported the first case of laser exposure to a vital human tooth. Unfortunately, these pioneer studies produced unfavourable results due to the adverse effects on hard dental tissues,[2–5] as well as the dental pulp from the primary laser beam.[4,5] Since then, there has been rapid development in laser technology for its use in both medical and dental sciences. However, it was not until 1989 that the first dental laser became available for commercial use after the discovery of Nd:YAG laser by Myers.[6]

To date, a range of laser systems has been used in dentistry, including argon, carbon dioxide (CO_2), Er:YAG, Er,Cr:YSGG, Nd:YAG, Ho:YAG, KTP and diode lasers. They have diverse applications in caries detection,[7–9] caries removal,[10,11] cavity preparation,[12,13] tooth bleaching,[14,15] root canal treatment,[16,17] periodontal treatment,[18,19] oral surgery,[20,21] implantology,[22,23] as well as in the dental laboratory.[24,25] Among these laser systems, Er:YAG laser seems to be promising. The Er:YAG laser is a solid state laser and uses Er^{3+} ions suspended in a complex crystalline matrix of Yttrium-Aluminium-Garnet (YAG) to provide electrons for excitation. Erbium is a metallic element of the rare earth group and occurs with yttrium. In Er:YAG laser, lasing occurs at a wavelength of 2.94 μm which falls in the middle infrared region of the electromagnetic spectrum. This emission wavelength is well absorbed by both water and hydroxyapatite resulting in effective ablation of enamel and dentine with minimal or no thermal damage to surrounding tissues.[26,27] The delivery systems of Er:YAG laser energy include non-glass rare earth optical fibres, waveguide or articulated arm.

Some studies have reported the effect of lasers on dental restorative materials.[28–32] Hibst and Keller[28] conducted clinical pilot studies on the effects of Er:YAG laser on dental cements, composites and amalgam. They found that the ablation efficiency of these materials was comparable to that of enamel and dentine and thus, sufficient for clinical applications. Since amalgam absorbs Er:YAG laser energy, the possible health hazards associated with the toxic release of mercury vapour in the escaping plume during amalgam ablation need to be considered.[28,29] Blum et al.[31] studied the effects of Nd:YAP laser on current restorative materials used for coronal restorations in endodontically treated teeth. Data from crater diameters and depths allowed them to classify the materials in terms of reactivity to lasing. They observed that the reactivity in decreasing order was temporary cement, composite, amalgam, polycarboxylate cement and prosthodontic alloy. Their studies also showed that the Nd:YAP laser was absorbed quickly by these materials and verified its potential use for the removal of these materials before or during endodontic retreatment.[31] Lizarelli and co-workers[32] compared the ablation rate between composite resins and dental hard tissues after Er:YAG irradiation. They found that the ablation rate of dentine in primary and permanent teeth was equal or superior when compared with the composite materials used. This was due to the high water content in the dentine. Thus, it may be difficult to minimise the effect of removing healthy dentine while removing old composite resin restorations; on the other hand, this was not the case for enamel in primary and permanent teeth. They concluded that ultra-conservative dentistry could only be applied for enamel.[32] In another study, Lizarelli et al.[33] examined the ablation rate and morphological aspects of different types of composite resins (microfiller, hybrid, and condensable) exposed to Er:YAG laser irradiation. The hybrid was found to be removed more easily and efficiently compared with the microfilled and condensable composite resins. They concluded that the ablation rate of the composite resins was dependent on the laser energy; whereas, the micromorphological aspects of the composite resins were dependent on their chemical composition and structure.[32]

There have been few reports on the use of Er:YAG laser to remove restorative materials,[28,32,34] but there is lack of data on the effects of its exposure on tooth-coloured dental restorative materials. If a successful laser technique can be developed to cut through these materials efficiently, then the use of Er:YAG laser system to do this selectively could be applied clinically, for example, when replacing existing dental restorations as an alternative to conventional handpiece. The aims of this study were to assess the surface morphology and to determine the ablation threshold of dental restorative materials following Er:YAG laser irradiation.

2. EXPERIMENTAL

2.1 Specimens

The materials used were commercially available unfilled resin (Delton; Dentsply), composite resins (Z100; 3M, Espe and P60; 3M, Espe), polyacid-modified composite resin (Dyract; Dentsply), resin-modified glass ionomer cements (Fuji II LC; GC Corporation and Vitremer; 3M, Espe) and glass ionomer cements (Fuji VII; GC Corporation and Fuji IX; GC Corporation) [Table 1]. They were dispensed and prepared according to the respective manufacturer's instructions. Split-custom moulds placed on glass slabs were used to make six cylindrical specimens (diameter 3 mm, depth 10 mm) for each material. These specimens were enough to provide 17 impact sites which corresponded to 17 different laser energy settings ranging from 40 mJ to 600 mJ. Coarse and medium abrasive Softlex discs (3M, Espe) were used to polish the surface of the specimens so that the laser irradiation could take place on flat surfaces.

Table 1: Dental restorative materials used.

Material	Type of material	Polymerisation mode	Classification of material
Delton	Unfilled resin	Light-cured	Pit and fissure sealant
P60	Composite resin	Light-cured	Restorative material
Z100	Composite resin	Light-cured	Restorative material
Dyract	Polyacid-modified composite resin	Light-cured	Restorative material
Fuji II LC	Resin-modified glass ionomer	Dual-cured	Restorative material

(*continued on next page*)

Table 1 (continued)

Material	Type of material	Polymerisation mode	Classification of material
Vitremer	Resin-modified glass ionomer	Dual-cured	Restorative material
Fuji IX	Glass ionomer cement	Self-cured	Restorative material
Fuji VII	Glass ionomer cement	Self-cured	Restorative material Pit and fissure sealant

2.2 Laser Irradiation

An Er:YAG laser system (KEY Laser 3, Model 1243, KaVo Dental GmbH, Biberach, Germany) operating at a wavelength of 2940 nm with a pulse duration of 200 µsec in single pulse mode was used. The system has a laser head, water cooler and power supply with automatic control. Specimens were placed on the split-mould and a focused Er:YAG laser beam was delivered perpendicular to the flat surface of the specimens. The laser beam was delivered via a rare earth optical fibre to a sapphire window handpiece (Model 2061). The distance from the laser window to the specimen surface was approximately 7 mm. Six cylindrical specimens of each material were prepared to provide a total of 17 impact sites. The laser energy settings varied from 40 mJ to 600 mJ and laser irradiation was carried out without any water spray (dry laser). The surface morphology of the impact sites were examined using Olympus binocular dissecting microscope (Model BH-2, Olympus, Tokyo, Japan) and scanning electron microscope (Model JSM-6460LA, Japan Electron Optics Ltd, Japan). The scanning electron microscope used in this study has an electron back-scattered diffraction pattern detector camera to provide crystallographical details. The impact sites were graded qualitatively as nil, ablation, fusion, combustion or various combinations of these. All impact sites were photographed by a 3.3 megapixel digital camera (Coolpix 995, Nikon, Tokyo, Japan). The diameters of the impact sites were measured using the micrometer scale within the digital camera, whereas the depths of the impact sites were measured to an accuracy of 10 microns using a depth analogue micrometer (Mahr, TESA, Mitutoyo). Measurements for depth of each impact site were done three times and the mean values were recorded. There was only one operator who carried out all measurements. The ablation rate was measured volumetrically using the data from crater diameter based on the hemispherical shape of the crater (volume of hemisphere = $2/3\pi r^3$). Results of crater diameters, depths and volumes were plotted to compare the materials as a function of laser energy. All results were analysed using one-way analysis of variance (ANOVA). Turkey-Kramer multiple comparison test was carried out if $p < 0.05$. $p < 0.05$ and $p < 0.0001$ were considered as significant and extremely significant respectively. Two-sided significant tests were used throughout the analysis.

3. RESULTS AND DISCUSSION

3.1 Surface Morphology

All materials showed surface morphological changes after a single pulse of Er:YAG laser irradiation. The surface morphology was graded qualitatively as nil, ablation, fusion (melting), combustion (burning) and various combinations of these. In all materials except Delton, two distinct zones were evident: a central crater with or without combustion, surrounded by a peripheral white zone (fusion zone). At 40 mJ, Delton did not show any effect from laser treatment; however, ablation effects were only evident at laser energy from 60 mJ to 600 mJ [Figure 1(a)]. From 40 mJ through to 600 mJ, P60, Z100 and Dyract [Figures 1(b), (c), (d)] showed a combination of ablation and fusion, whereas Vitremer, Fuji II LC, Fuji IX and Fuji VII [Figures 1 (e), (f), (g), (h)] showed a combination of ablation, fusion, and combustion. Some similarities were observed when these restorative materials were grouped on the basis of their material science. The central zones of P60, Z100 and Dyract featured white areas, whereas in Vitremer, Fuji II LC, Fuji IX, and Fuji VII, the central zones displayed a combination of white and brown/black areas. The brown/black area represented combustion zone. The combustion effect increased with increasing laser energy. In summary, there was a clear trend in the irradiated surface morphology of these materials in that, Delton, which has very low filler content, exhibited ablation effect only. In contrast, fusion and ablation effects were seen in materials which are primarily resin (P60, Z100, Dyract). Towards the end of the material spectrum of resin-modified glass ionomers and conventional glass ionomer cements which are primarily glass ionomers, a combination of ablation, fusion and combustion effects were observed.

The different morphological zones displayed by different materials can be explained as follows: the crater represents the maximum thermal energy of the laser. Because the highest energy concentration is in the centre of the impact site, materials from this area melted and were pushed outward from the central area where they then fused with the materials surrounding the crater. The analogy of this effect is similar to an erupting volcano where all the lava is being expelled and scattered to its surroundings. Thus, the fusion zone represents the union of materials from the central area with the materials outside the crater.[31] Delton showed ablation effects only because it has a very low filler loading by weight (1.08%) in the resin matrix. No fusion zone was apparent in the presence of minimal filler content. On the other hand, the rest of the materials with higher filler loading of about 65% by weight (according to the material safety data sheet) displayed fusion zones. P60 and Z100 have identical ablated surface morphology because their inorganic fillers are essentially the same. The size distribution of zirconia/silica particles in P60 and Z100 is in the range of 0.01 to 3.5 µm and 0.01 to 3.3 µm respectively, with an average particle size of 0.6 µm.

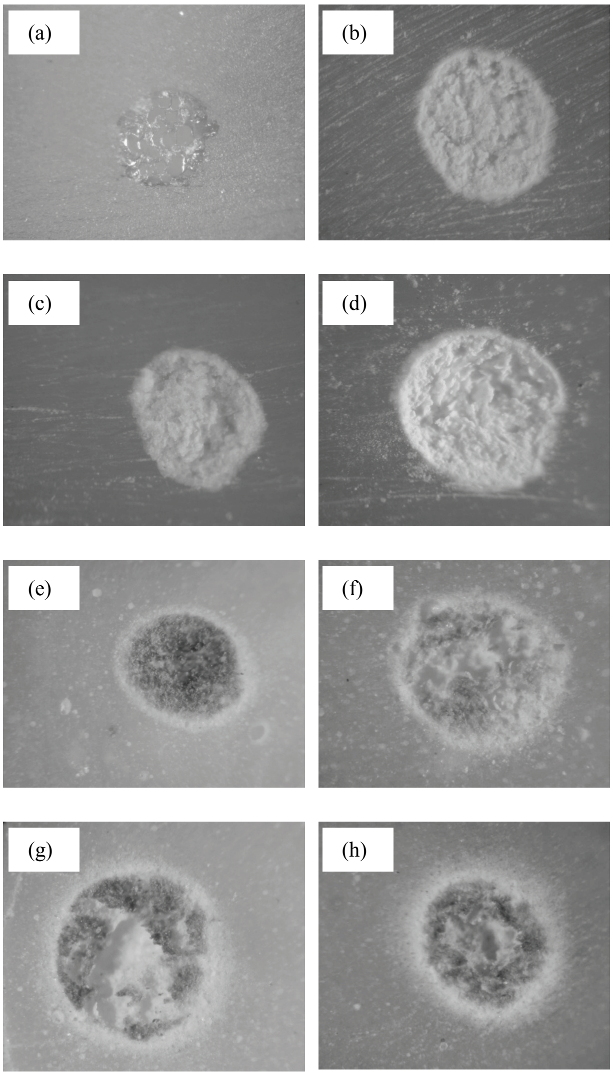

Figure 1: Stereo micrographs of: (a) Delton (25X), (b) P60 (30X), (c) Z100 (25X), (d) Dyract (40X), (e) Vitremer (40X), (f) Fuji II (30X), (g) Fuji IX (40X), and (h) Fuji VII (25X) ablated by Er:YAG laser at 200 mJ.

Dyract is a polyacid-modified composite resin (compomer) which contains fluoroaluminosilicate glass and resin matrix. Although compomer has a combination of characteristics of both composite resin and glass ionomer, the amount of glass ionomer component is very low. Therefore, Dyract showed similar surface morphology to composite resins (P60 and Z100). These three materials exhibited ablation and fusion effects only. Fuji IX and Fuji VII are conventional glass ionomer cements (GIC), whereas Vitremer and Fuji II LC are glass ionomer cements with the addition of a small quantity of resin, hence, resin-modified glass ionomer cements (RMGIC).

According to their manufacturers, the percentages by weight of fillers in these materials are: Vitremer (fluoroaluminosilicate glass 90%), Fuji II LC (fluoroaluminosilicate glass 100%), Fuji IX (aluminosilicate glass 95%) and Fuji VII (aluminosilicate glass 100%). The reason for combustion zones in RMGIC and GIC could be due to the very high content of aluminosilicate glass particles. Thus, combustion zone was not observed in materials containing predominantly resin matrix (Delton, P60, Z100, Dyract). Hibst and Keller[28] observed that ablation of filling materials revealed strong signs of thermal interactions. These were manifested by the brownish discolouration of materials which was interpreted as carbonisation.

Scanning electron micrographs (SEM) at 100X (Figure 2) and 500X (Figure 3) magnifications showed that the surface morphology of Delton appeared as multiple, clear-looking "bubbles". Due to the very low filler loading, the ablated surface looked smooth. On the other hand, the irradiated P60, Z100, Dyract, Vitremer, Fuji II LC, Fuji IX and Fuji VII showed irregular serrated surfaces. The inclusion of filler and glass particles in these materials contributed to the serrated surface morphology. These findings were consistent with previous study which found that micromorphological aspects of different types of composite resins exposed to Er:YAG laser was dependent on their chemical composition and structure.[33] Surface cracks were also present in the peripheral areas of ablated Vitremer, Fuji II LC, Fuji IX and Fuji VII. In all materials, the periphery of the ablated area was clearly delineated from the non-ablated surface (Figure 3). On top of that, fluorescent aluminosilicate glass particles were observed in the SEM of composite/glass ionomer hybrid and glass ionomer materials.

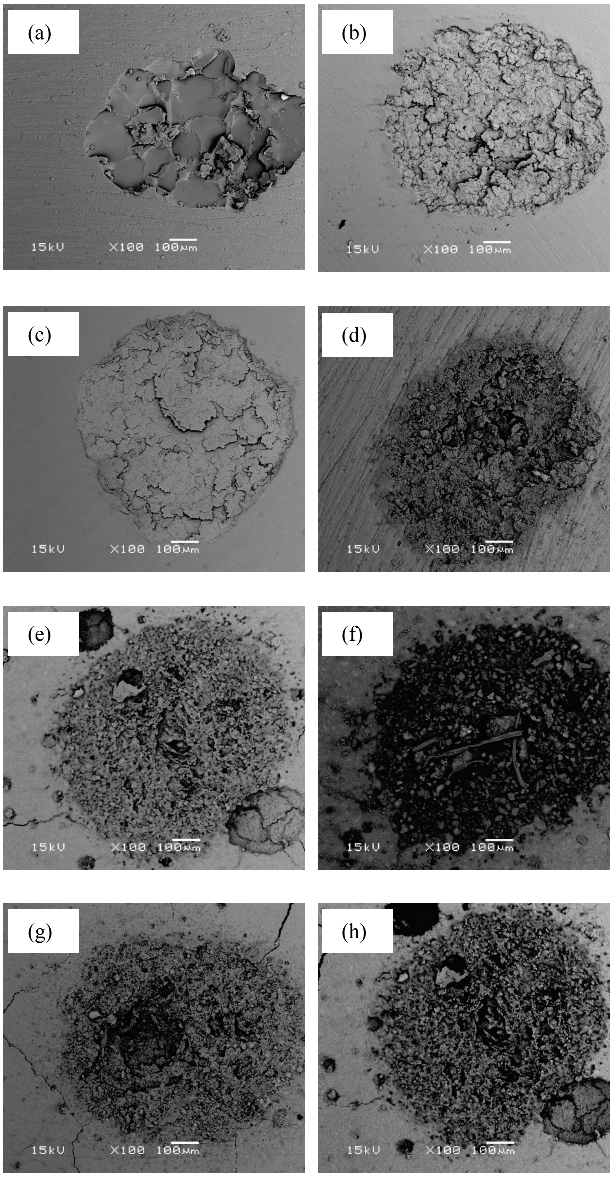

Figure 2: Scanning electron micrographs of: (a) Delton, (b) P60, (c) Z100, (d) Dyract, (e) Vitremer, (f) Fuji II, (g) Fuji IX, and (h) Fuji VII, ablated by Er:YAG laser at 200 mJ, 100X magnification.

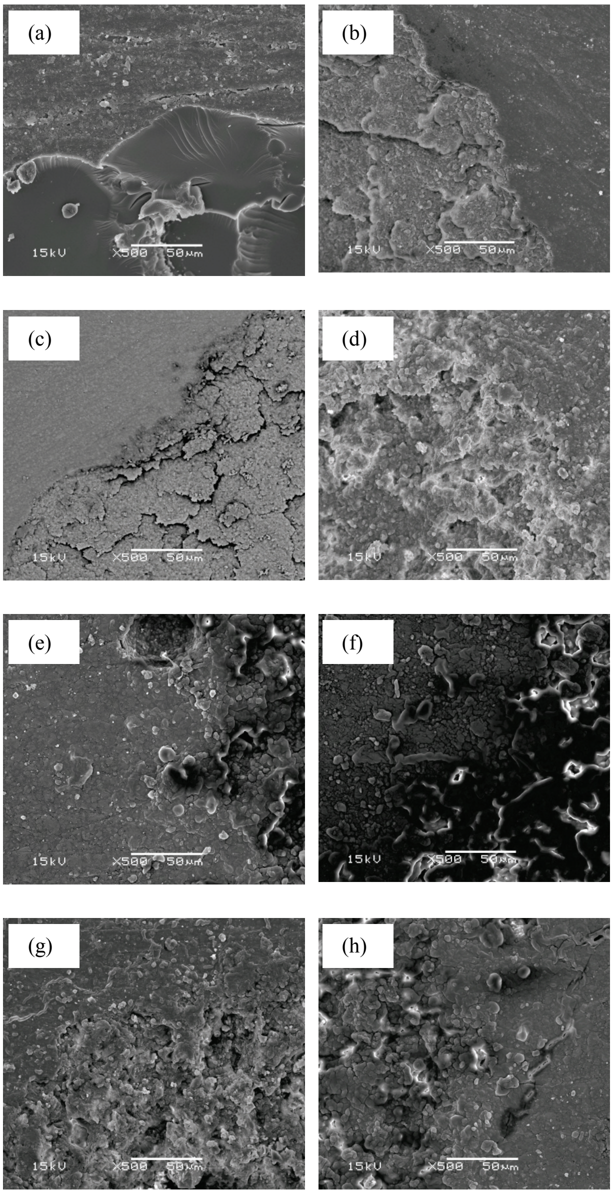

Figure 3: Scanning electron micrographs of: (a) Delton, (b) P60, (c) Z100, (d) Dyract, (e) Vitremer, (f) Fuji II, (g) Fuji IX, and (h) Fuji VII, ablated by Er:YAG laser at 200 mJ, 500X magnification.

3.2 Crater diameter, Depth and Volume

Figures 4 and 5 showed that both crater diameters and crater depths increased with increasing laser energy. In Figure 4, only three materials (P60, Vitremer, Fuji VII) displayed crater diameter of 0.8 mm at 600 mJ, which was the maximum laser energy used. Thus, the rest of the materials would require laser energy above 600 mJ to achieve the maximum diameter of the laser beam (0.8 mm). Accordingly, the maximum crater diameter was limited by the diameter of the laser beam used in this study. In addition, Vitremer was the only material that exhibited plateau effect from 500 mJ onwards. Figure 5 revealed that all materials formed a crater at 40 mJ except Delton. Hence, the ablation threshold (energy at which surface ablation begins) of all materials was 40 mJ except Delton, which showed crater formation at 60 mJ. When the graph of log crater volume was plotted against laser energy (Figure 6), a similar pattern of exponential increase was observed from 40 mJ to 100 mJ for all materials except Delton. Delton displayed a steep logarithmic increase above 100 mJ. The logarithmic increase indicated that there was a high correlation between crater volume and laser energy.

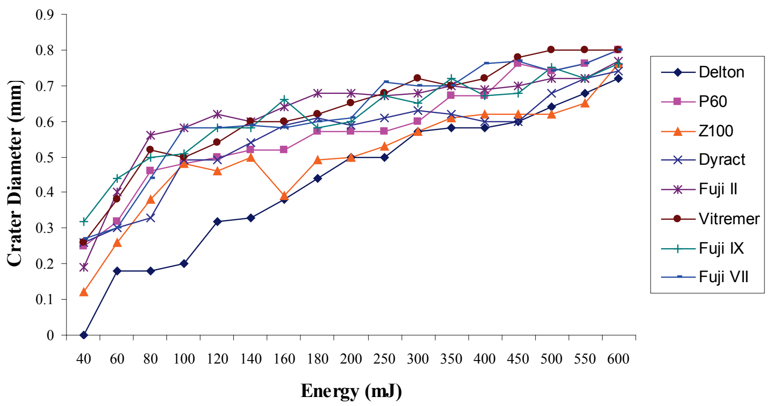

Figure 4: Crater diameters of dental restorative materials vs Er:YAG laser energy.

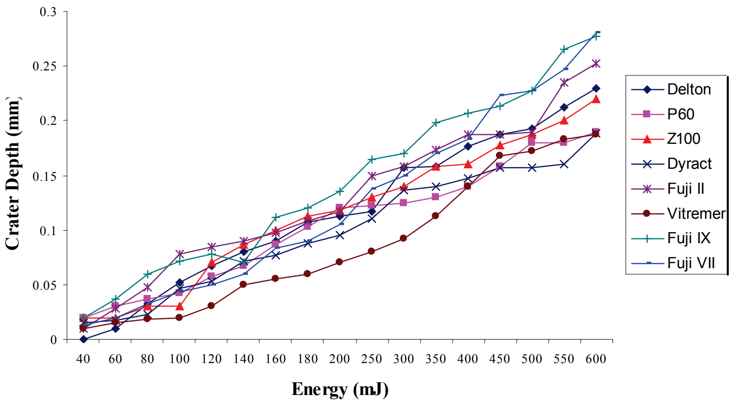

Figure 5: Crater depths of dental restorative materials vs Er:YAG laser energy.

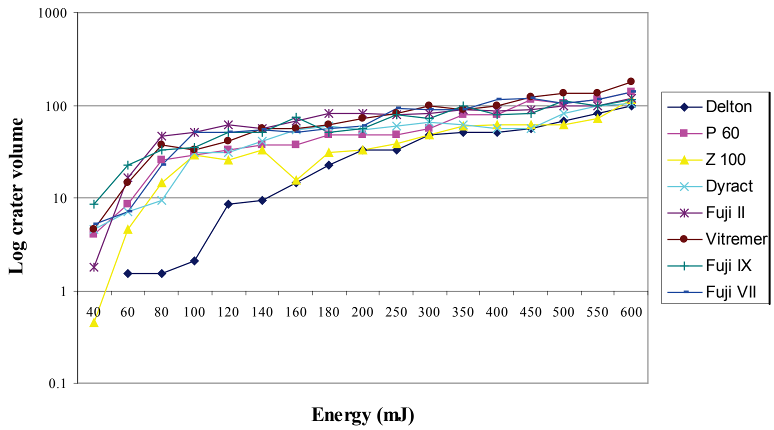

Figure 6: Log crater volume of dental restorative materials vs Er:YAG laser energy.

Data of mean differences and standard deviation were used to ascertain which material produced the biggest crater, the deepest crater and the largest crater volume. Tables 2, 3 and 4 classified dental restorative materials according to their reactivity to Er:YAG lasing and showed that there were statistically significant differences in crater diameter, crater depth and crater volume respectively between some materials ($p < 0.05$). When these materials were ranked according to the degree of significance, Delton demonstrated the smallest crater, whereas Vitremer demonstrated the biggest crater. In terms of crater depth, Vitremer demonstrated the shallowest crater, while Fuji IX demonstrated the deepest crater. Delton and both Vitremer and Fuji VII had the smallest and the largest crater volumes respectively.

Table 2: Comparison of lasing reactivity between dental restorative materials based on crater diameter.

Materials	Delton	P60	Z100	Dyract	Fuji II LC	Vitremer	Fuji IX	Fuji VII	Lasing reactivity[ↄↄ]
Delton		***	***	***	***	***	***	***	A
P60	***		***	NS	*	*	NS	NS	CD
Z100	***	***		*	***	***	***	***	B
Dyract	***	NS	*		***	***	**	**	C
Fuji II LC	***	*	***	***		NS	NS	NS	DE
Vitremer	***	*	***	***	NS		NS	NS	E
Fuji IX	***	NS	***	**	NS	NS		NS	D
Fuji VII	***	NS	***	**	NS	NS	NS		DE

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$
NS not significant
ↄↄ materials are ranked based on reactivity to lasing
A (smallest crater) → E (biggest crater)

Table 3: Comparison of lasing reactivity between dental restorative materials based on crater depth.

Materials	Delton	P60	Z100	Dyract	Fuji II LC	Vitremer	Fuji IX	Fuji VII	Lasing reactivity[ↄↄ]
Delton		NS	NS	*	NS	***	***	NS	C
P60	NS		NS	NS	***	**	***	*	B
Z100	NS	NS		NS	NS	***	***	NS	BC
Dyract	*	NS	NS		***	NS	***	***	AB
Fuji II LC	NS	***	NS	***		***	NS	NS	CD
Vitremer	***	**	***	NS	***		***	***	A
Fuji IX	***	***	***	***	NS	***		**	D
Fuji VII	NS	*	NS	***	NS	***	**		C

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$
NS not significant
ↄↄ materials are ranked based on reactivity to lasing
A (shallowest crater) → D (deepest crater)

Table 4: Comparison of lasing reactivity between dental restorative materials based on crater volume.

Materials	**Delton**	**P60**	**Z100**	**Dyract**	**Fuji II LC**	**Vitremer**	**Fuji IX**	**Fuji VII**	**Lasing activity**①①
Delton		***	NS	***	***	***	***	***	A
P60	***		***	NS	NS	***	NS	***	C
Z100	NS	***		NS	***	***	***	***	AB
Dyract	***	NS	NS		***	***	***	***	BC
Fuji II LC	***	NS	***	***		NS	NS	NS	CD
Vitremer	***	***	***	***	NS		NS	NS	D
Fuji IX	***	NS	***	***	NS	NS		NS	CD
Fuji VII	***	***	***	***	NS	NS	NS		D

* $p < 0.05$
** $p < 0.01$
*** $p < 0.001$
NS not significant
①① materials are ranked based on reactivity to lasing
A (smallest volume) → D (largest volume crater)

The ablation threshold of materials can be explained from cohesive and adhesive forces between molecules in filler particles, glass particles and polymer matrix. At 40 mJ, the laser energy was sufficient to break the cohesive and adhesive bonds in all materials except Delton. The high degree of crosslinking between dimethacrylate monomers in Delton matrix created a strong intermolecular bond which resulted in resistance to ablation at this energy level. Thus, the high cohesive forces between the monomers explained why Delton has a higher ablation threshold compared to other materials. There was a clear trend that glass ionomer cements and resin-modified glass ionomer materials produced big craters compared with other materials that were predominantly resin matrix. The high percentage of water by weight in GC Fuji IX Capsule – Liquid (50%), GC Fuji VII Capsule – Liquid (50%), GC Fuji II LC Capsule Liquid (20–30%) and Vitremer Core Buildup/Restorative Liquid (25–30%) was responsible for these effects. Materials with high water content allowed efficient absorption of Er:YAG laser energy which resulted in less penetration and thus, produced big craters. Contrariwise, it would be expected that materials with low water content such as Delton, composite resins and polyacid-modified composite resin produced small craters (Table 2). In particular, Delton, which has no water as an ingredient demonstrated the smallest crater. A similar study that found the correlation between water content and size of ablation was carried out by Lizarelli et al.[32] who observed that the ablated area for dentine was always bigger than enamel because of the higher water content in dentine compared with that in the enamel resulting in less penetration and greater ablation.

The rate of material removal (ablation rate) was represented by crater volume. Results from both Table 2 and Table 4 showed similarity in that Delton demonstrated the smallest crater, as well as crater with the least volume. On the other hand, Vitremer demonstrated the biggest crater, as well as crater with the largest volume along with Fuji VII. These observations were valid because data of crater volume was estimated from crater diameter based on the hemispherical shape of a crater (volume of hemisphere = $2/3\pi r^3$). It can be concluded that materials with high water content exhibited high ablation rates and big craters.

In Table 3, Vitremer and Fuji IX exhibited the shallowest and the deepest crater respectively. Glass ionomer cements and resin-modified glass ionomer materials with the exception of Vitremer demonstrated considerable crater depth which was consistent with weak absorption of laser energy. The inclusion of aluminosilicate glass in Fuji II LC, Fuji IX and Fuji VII absorbed laser energy less efficiently and thus, laser energy is available to result in deeper penetration. It would be expected that Vitremer, which is a resin-modified glass ionomer demonstrated similar findings to Fuji II LC, however, that was not the case. This could be due to the dissimilarity of filler particles in Vitremer which displayed strong absorption of laser energy, resulting in the shallowest crater. Thus, the lasing reactivity of dental restorative materials is dependent on their chemical compositions.

4. CONCLUSION

All dental restorative materials showed changes in surface morphology following Er:YAG laser irradiation. The surface morphology changes varied from nil effect, ablation, fusion, combustion and various combinations of these. The ablation threshold of all materials was 40 mJ except Delton (60 mJ). Materials with high water content demonstrated high ablation rates, as well as craters with big diameters and volumes. In addition, materials that absorbed laser energy weakly demonstrated deep craters. In view that all restorative materials used in this study absorbed Er:YAG laser, this laser system has a great potential in restorative dentistry and can be utilised as an alternative to conventional rotary instrument when removing old restorative materials. However, further investigations are necessary to compare the ablation rates between these restorative materials and dental hard tissues.

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