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LASER ETCHING OF ENAMEL SURFACES, BOND STRENGTH AND SEM EVALUATION

by

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Submitted in partial fulfillment of the requirements for the

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Abstract

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It has been suggested that laser etched enamel surfaces may produce comparable bond strengths to that of acid etched surfaces. Therefore, a study was conducted to (1), compare the bond strength acheived with laser and acid etching and (2), to evaluate the surface characteristics of laser, acid, and non-etched enamel with the aid of scanning electron microscopy (SEM). Seventy-one recently extracted bovine incisors were randomly divided into four groups. Twenty-one teeth were etched with 37% phosphoric acid. Twenty teeth were etched with a Nd:YAG laser. Eighteen teeth were etched with a carbon dioxide laser and 12 nontreated teeth were used as a control. Orthodontic brackets were bonded to the prepared enamel surfaces and the shear bond strengths of each sample were recorded with a universal testing instrument. The debonded brackets and enamel surfaces were reviewed under a light microscope and the point of bond fracture determined. The treatment surfaces were also evaluated with the aid of SEM. Results from the study showed: (1) Acid etching produced a much higher bond strength than either

the Nd:YAG or Carbon dioxide lasers. (2) The Nd:YAG laser produced a higher bond strength than the Carbon dioxide laser. (3) Under SEM evaluation the surface of the acid etched enamel was different than either laser group. (4) Under the conditions of this study, bond strengths of the laser etched surfaces were not clinically acceptable.

DEDICATION

to

My wife Laurie and my sons Andrew
and T.J. for their commitment and love.

My mother and father and my brothers
for their support and encouragement
that made my education possible.

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INTRODUCTION

The process of etching enamel surfaces has revolutionized dentistry and changed many of the procedures used in orthodontics. Bonded brackets, with sufficient strength to withstand the forces of occlusion and the mechanical forces from orthodontic wires are now routinely used in orthodontic practice. Thirty seven percent phosphoric acid has been the etching material of choice and much research has been done on bond strength, as well as determining the physical characteristics of the etched enamel surface. With the development of the laser, many conventional techniques used in dentistry are being reevaluated. Recently attention has been focused on the ability of the laser to change enamel surface characteristics. There have been reports in the literature describing similarities between lased enamel and acid etched enamel. However before the laser can be effectively used for this purpose it must be evaluated for safety and utility. Safety issues include potential damage to the soft tissues and the pulp as well as potential damage to the operator.

The hypothesis of this study is that laser etching is a viable substitute for acid etching of enamel in preparation of bonding orthodontic attachments. Laser etching of enamel will produce similar bond strengths to that of acid etched enamel with a high degree of efficacy.

The objectives of this study were to (1), compare the bond strengths achieved of laser etching and acid etching and (2), to evaluate the surface

characteristics of the laser etched, acid etched and non-etched surfaces under a scanning electron microscope (SEM).

Two commercially available lasers, American dental lasers Nd:YAG laser (American Dental Laser, 280 North Woodward Ave., Suite 216, Birmingham Mi 48009) and Luxars carbon dioxide laser (Luxar Corporation, 11816 North Creek Parkway, Suite 102, Bothell WA 98011) were used. Both are FDA approved for use on oral soft tissue and are presently being evaluated for use on dental hard tissue. The in vitro methods used in this study were carefully chosen to follow closely the technique that would most likely be used in a clinical setting. The experimental design controlled for all factors including consistent enamel surfaces, etching and bonding procedures, bracket and composite type and environmental conditions.

LITERATURE REVIEW

The basic thought patterns concerning light and relativity began with Albert Einstein. In 1917 Einstein described in mathematical terms how areas of the electromagnetic field could be stimulated to emit light that was amplified. Einstein's theory of stimulated emission was used by Schwalow and Townes[1] in 1958. These researchers used optical resonators and applied Bohr's theory to investigate and theorize on the principles of microwave emissions called maser (microwave amplification by stimulated emission of radiation). Bohr's theory states that atoms can exist for a certain amount of time in definite electronic orbits. If an electron moves from a higher orbit to a lower orbit monochromatic radiation is released. In the paper they published they discussed using the maser principles in the optical region of the electromagnetic field.

T.H. Maiman[2] in 1960 was the first to stimulate light to emit amplified radiation. He coined the term laser which is an acronym which stands for light amplification by stimulated emission of radiation. By inserting a ruby rod into a flash lamp he was able to excite the electrons to emit photons thus generating the first laser beam. His original research was accomplished in the Hughes Research laboratory. In 1961 Javan et al.,[3] developed a continuously operating laser and also developed the first gas laser using a helium neon mixture. In 1964 Patel et al.,[4] described the first carbon dioxide laser. Today there are more than 600 known laser media. All emit laser

radiation of different wavelengths.

Lasers in Medicine

Lasers have been used in medicine for many years and are being increasingly utilized in areas where uncontrolled bleeding and access may be a problem. There are approximately 10 different types of lasers used in medicine two of which are the Nd:YAG laser and carbon dioxide laser. The surgical specialties of otolaryngology, plastic surgery, ophthalmology, neurosurgery, and others routinely utilize lasers in place of the scalpel. In the early 1960's argon lasers were used on the retina especially in diabetics and in glaucoma treatment.[5] Gynecologists routinely use the carbon dioxide laser to remove precancerous lesions of the cervix.[6] Otolaryngologist have used the carbon dioxide laser to remove vascular lesions from the very small and confined area of the larynx.[7] The Nd:YAG laser has been used to treat bleeding ulcers and tumors of the gastric tract and pharynx.[8,9] Laser photodynamic therapy of certain cancers has been used successfully. After the tumor is injected with a photosensitizer the laser is used to selectively destroy the cancer tissue.[10] Many studies have been conducted investigating the analgesic effects of soft laser radiation.[11] This involves the use of very low powered lasers which emit radiation in the near infrared or visible spectrum. There are also some preliminary reports using low powered lasers to promote wound healing. A comparison has been made between laser use and that of electrosurgery,[12] scalpel surgery[13] and cryosurgery.[14] Vaughan and Strong both published multiple papers on the use of the carbon dioxide laser in treating pathologic lesions of the larynx.[15,16,17]

Some advantages of the laser over other surgical devices include control of bleeding, sterilization, decreased pain, less post surgical wound contraction and less postoperative swelling. Some disadvantages of the laser include initial decreased tensile strength of the tissue, possible injury to adjacent tissues, and possible damage to the operators eyes.[18]

Lasers and Dentistry

While lasers have been used in medicine for over thirty years, mostly on soft tissue involving the removal of pathologic lesions, its use in dentistry has been limited. This is surprising considering the many advantages that a laser has over other techniques used in dentistry. The laser is particularly useful in areas in which access is a problem because the laser beam can be very small and easy to manipulate. Thus one would think that the lasers application in dentistry with it's focus on the small confined oral environment would be more widespread. Clinical use of the laser in dentistry is starting to grow, especially with the introduction of American Dental Lasers Nd:YAG laser and Luxars carbon dioxide laser. Both of these lasers are Food and Drug Administration (FDA) approved for use on soft tissue.

Many research papers have been published evaluating the lasers effects on both hard and soft tissue. Possible uses in dentistry include sealing enamel fissures, etching enamel and dentin, removing caries, fuzing cracks, sealing root canals, holography, and analgesia.[19,20,21,22] More recently lasers have been used in oral and maxillary surgery.

In the late 1970's the carbon dioxide laser was applied to oral pathologic lesions and to gingival tissue removal. The carbon dioxide laser and other medical lasers were not used on hard tissue such as teeth

because the lasers high energy caused the nerves in the tooth pulp to die.

Effects on Enamel

When lasers were first introduced it was felt that they would soon replace the dental drill as a means of cavity preparation. It did not take long for reality to sink in and the laser's limitations to be realized. Stern and Sognnaes in 1964,[23] studied the effects of various lasers including the carbon dioxide laser on tooth enamel. They concluded that the high energy produced excessive heat which damaged the dental pulp.

Further research on dental hard tissues was conducted by Stern et al.[24,25] in 1966 and 1972. They demonstrated that there may be an increase in the acid resistance of tooth enamel exposed to laser radiation. The experimenters used a pulsed carbon dioxide laser on human dental enamel and looked at the microscopic enamel surface changes at various energy densities ranging from 13 to 50 joules per square centimeter. They also looked at the enamel surface under the SEM. Those samples that were exposed to 50 joules per square centimeter exhibited surface crazing and mottleling with white surface opacities and light brown discoloration. Under SEM examination surface flaking, cracks and also fissures were seen. Pores as wide as 1 micron were also seen. It was suggested that the surface in certain areas had actually melted and resolidified. At 25 joules per square centimeter slight crazing and surface opacity was seen. Under SEM the enamel looked like a fine crust with some cracking. At 13 Joules per square centimeter no gross changes were visible and only slight alterations were found under SEM observation. The laser was focused at a 5 millimeter spot size with 50 nanosecond pulses about 100 milliseconds

apart. They concluded that at all three energy levels surface demineralization was inhibited. They theorized that it was the fusion of the pores that caused the inhibition.

Johanna Vahl,[26] used a ruby laser at 0.6943 microns and 1 watt of energy emission from the power supply to produce an excitation energy of 500 watts with a 270 nanosecond pulse. He lased human tooth enamel and conducted SEM studies. Vahl also looked at the vapor cloud or plume that was produced when the laser beam hit the enamel surface and using X-ray crystallographic methods evaluated the clouds contents. It was found that the areas adjacent to the lased enamel were unchanged while the areas hit by the laser formed craters which had a melted appearance. The vaporized material looked like melted drops and spheres which had the appearance of bursted shells. Particle size varied from 1.0 to 0.12 microns in diameter. They concluded that some of the tooth surface is melted and sprayed out by the pressure of the evaporated material. X-ray crystalography showed that these particles consisted of tricalcium phosphate, not hydroxyappetite.

In 1965 Goldman and Gray[27] using a pulsed ruby laser at a 0.6948 micron wavelength and with high energy densities ranging from 4,000 (unfocussed beam) to 13,400 (focussed beam) joules per square centimeter showed deep penetration of the laser beam. They found that laser application to carious regions caused destruction of the lesion, especially colored lesions which they concluded absorbed more of the energy. The focussed beam had a much deeper penetration than the unfocussed beam. They also experimented with a Q-switching technique to lower the peak power and found a substantial decrease in effect. Q-switching is used to

obtain a fairly consistant pulsed beam. Evaluation of extracted teeth using a thermister in the pulp cavity showed a maximum temperature rise of 29 degrees Celsius with laser energy application of 4,000 joules per square centimeter.

Varner et al.,[28] in 1967 published results on a study that evaluated the effect of laser application to various colored stains placed on enamel. Using a low powered ruby laser with an energy output of approximately 0.6 joules, they lased enamel coated with blue, green, and black stains. When the laser beam was applied to the enamel, impact craters were formed. They found that the green dye effect was similar to that of acid etching which showed a pitted appearance. They felt the effect was due to the fact that the enamel rod picks up more stain. Therefore this area would absorb more laser light and show a greater effect.

A comparative study on the effects of laser radiation on enamel and dentin comparing a ruby laser with a carbon dioxide laser was completed in 1968 by Lobene et al.[29] They found that the enamel changes were different with a continuous wave carbon dioxide laser at 10.6 microns compared to the pulsed ruby laser functioning at 0.6943 microns. These researchers reported a lack of gross cavitation with the carbon dioxide laser compared to the ruby laser. However, the carbon dioxide laser did damage the adjacent enamel. They postulated that the damage was caused by heat production. Unlike the ruby laser, the carbon dioxide laser also caused damage to the dentin. The energies used were relatively high and the continuous wave used produced a large build up of heat. They also looked at the x-ray diffraction patterns of irradiated powdered enamel and found the presence

of alpha calcium orthophosphate. They concluded that the molecular changes from hydroxyappetite were caused by the high temperatures.

Kantola et al.,[30] in 1973, published a study where they evaluated all the compounds found in lased then powdered enamel. They compared this sample with unlased enamel. They concluded that there was alpha calcium orthophosphate present in the lased enamel and not in the normal enamel. Alpha calcium orthophosphate is the high temperature form of the apatite phase of tricalcium phosphate. In a subsequent study, Kantola[31] looked at lased dentin and found that most of the organic material was burned off and that the dentin had a similar composition as enamel.

In 1973, Yammoto and Ooya[32] used a Neodymium doped (YAG) laser to evaluate the surface changes that occur after lasing of enamel. They also looked at the effect of demineralization on lased and unlased teeth. They used a Q-switched YAG laser with a repetition rate of 10 pulses per second, a wavelength of 1.06 microns, a spot size of 5 millimeters, an individual pulse time of 30 nanoseconds and a total energy density of 10 to 20 joules per square centimeter. The enamel surface lased at 10 joules per square centimeter showed clefts and partly fused micropores and a finely roughened surface. At 20 joules per square centimeter the surface was generally very smooth with a slightly rough porous appearance with almost completely fused micropores. They further found that lased enamel surfaces were much more resistant to demineralization than unlased surfaces both at 10 and 20 joules per square centimeter. Other studies looked at the effect of laser irradiation on caries prevention and concluded that the laser is indeed effective for this purpose.[33,34]

In 1977 Boehm et al.,[35] measured the thermal effects and surface cracking associated with a continuous wave carbon dioxide laser. Human teeth were irradiated with the laser at various exposure times and intensities and then assessed as to the amount of enamel damage. They found that at temperatures above 782 degrees Celsius, evidence of apparent enamel melting was seen. This temperature is very close to the melting point of hydroxyappetite. They did not see any cracking for energy densities lower than 23.5 joules per square centimeter and found increasing surface cracking as the beam energy density increased from this power level. He also felt that there was an age factor and that older teeth have a lower cracking threshold.

In 1987 Nelson et al.,[36] conducted a study on the effects of low energy carbon dioxide irradiation on enamel. In this study they looked at four wavelengths. They evaluated the surface morphology and crystallography of the enamel surface. Polarized light microscopy and microradiographs along with reflected light microscopy and SEM and Infrared spectroscopy were all used to evaluate the enamel. They found that rapid melting of the surface enamel occurred with recrystalization of various calcium phosphate phases and that temperatures varied at the surface from 1,050 to 810 degrees Celsius. The surface melt also consisted of well crystalized, large, acid resistant particles of up to 0.5 micron in size. They measured the depth of melted enamel and found it to be around 5 microns. They also found a denatured organic zone that was affected to around 10 to 20 micron below the surface.

Myers and Myers,[37] in their study on removing incipient caries with a

Nd:YAG laser, found that the laser was able to remove both organic and inorganic debris from the pits and fissures of a tooth without damaging the pulp or the enamel. They used a mode-locked Neodynium doped YAG laser with a 1.06 nm wavelength, a 30 picosecond pulse duration, a repetition rate of 1 pulse per second, and a 50 micron spot size. They noted that during the lasing process a small white cloud or plume was produced about 1 cm high and 1 cm wide as the lesion was vaporized. They also reported hearing an occasional popping sound. SEM evaluation revealed that the lased enamel had a clean pitted appearance. It was also noted that since the time required to initiate a pain impulse is around 200 milliseconds, the Nd:YAG's very short pulse rate of 30 picoseconds would be too short to illicit pain. This was found to be true in an in vivo study published later by Myers[38] in 1985.

In 1988 Goultschin et al., studied the effects on both teeth and gingivae of dogs after the application of a continuous mode 10 watt carbon dioxide laser. They performed a laser gingivectomy and then looked a the adjacent enamel and cementum surfaces. They found that craters of 20 to 40 microns were formed in both cementum and enamel and, that after healing, the cementum craters were filled in with periodontal ligament fibers while the enamel craters were filled with bacteria. They also compared the gingival healing with that of scalpel surgery and found that with the laser there was less bleeding and similar healing. They did have a problem with the accuracy and the ability to manipulate the hand piece and felt that if they had more control that there would not have been as much enamel damage.

In 1989 Ferreira et al.,[39] reported on the light microscopy and SEM analysis of the effects of a continuous wave carbon dioxide laser applied to

enamel. There observations included extensive crazing and cratering of the enamel. They also observed rough exposed enamel that they felt was a result of the removal of the top layer of crazed or cratered enamel. The type and extent of the changes were directly related to the energy density which had a range of 0.8 to 200 joules per square centimeter. They also found that there was a relation to enamel prism orientation with a greater effect on cratering and crazing when the beam was directed perpendicular to the enamel rods. Rough exposed enamel, however occurred more when the beam was parallel suggesting that at this direction of laser beam application a flaking off or ejection of the top enamel layer occurred. They estimated the depth of the crazed and cratered enamel to be 2 to 11 microns. They also suggested that the enamel near the dentoenamel junction was more sensitive to laser irradiation possibly due to the increase in ability to become birefringent. They feel that the expansion and contraction that is caused by thermal buildup and the effect of shockwaves are both causes of cracking. With the lower energy densities used in this experiment it was found that only apatite crystals were found in the melted regions and no other phases such as alpha tricalcium phosphate or tetracalcium diphosphate were detected.

Effects on Enamel Soluability

Goodman and Kaufman[40] in 1977 looked at the X-ray diffraction pattern of sodium flouride coated lased enamel. They concluded that a recrystalization of the surface enamel occurred integrating the sodium fluoride in the form of fluoroappetite. The surface was then determined to be less soluble than the original enamel.

Yamamoto and Sato[41] in 1980 published a paper concerning caries prevention using the Nd:YAG laser. In this study they used a flexible optical fiber to apply the laser beam. They coated the teeth before irradiation with an absorptive material. They found that the lased area showed a high resistance to demineralization. The temperature rise measured in the pulp was 20 degrees Celsius, going from a normal pulp temperature of 37 degrees Celsius to 57 degrees Celsius. The exposure time was only 1 second which they felt was below the threshold that would cause pulpal damage.

In an article by Nelson et al.[42], he reflected on the concept that pulsed lasers allow you to increase the peak power density while keeping the pulse energy density constant thus confining the fusion, melting and recrystalization of the enamel to a thin surface region without harming the pulp or the deeper underlying enamel and dentin. Because enamel absorbs so well in the infrared region from 9.0 to 11.0 nanometers the carbon dioxide laser is very efficient. Under SEM evaluation they found that at energy densities of 50 joules per square centimeter, extensive surface roughening was produced to a depth of 5 microns. The 9.32 and 9.57 micron lines produced the greatest roughening effect with the 10.59 micron line producing the smoothest surface. The author gave three possible explanations for the decrease in demineralization of the lased enamel over unlased enamel and he felt that it is most probably a combination of the three. First the surface may become less permeable, second the surface may become less soluble and thirdly the destruction of the organic matrix may play a role.

Fowler and Kuroda[43] in 1986 compared heated enamel with laser irradiated enamel and also looked at their effects on solubility. They found that a heat gradient was formed from the enamel surface down to the pulp and that various changes in the enamel and dentin occur and that these changes were comparable to those found in furnace heating data.

Tagomori and Morioka[44] in 1989 looked a laser induced acid resistance of enamel in conjunction with flouride application. Using a pulsed Nd:YAG laser they found that after irradiation there was a greater amount of flouride uptake in the enamel. This was evaluated using an electron probe microanalyzer. A black initiator was applied prior to laser application. The enamel exposed to an energy level of 30 joules per square centimeter was shown to be fused within the first 5 micron and that cracks in the enamel occurred at 10 to 20 micron intervals with the cracks being less than 0.3 micron in width and reaching 60 to 70 micron in depth. It was at this energy density where the flouride uptake and acid resistance was at a maximum. A follow up paper in 1990 looked at possible mechanisms for the increased demineralization resistance.[45] Their conclusions were based on optical properties, compositional and structural changes and permeability studies. They felt that the high positive birefringence of lased enamel suggested that microspaces were formed in the enamel. They also found a decrease in lattice strain and a slight a-axis contraction occurred after lasing. The ions that are released by decalcification may be trapped in these microspaces whereas in unlased demineralization the ions diffuse out into the surrounding solution. They also found that the diffraction peaks became sharper with increasing temperature and energy density.

In 1985, Stewart et al.,[46] used a carbon dioxide laser to attach hydroxyappetite to an enamel surface. It was felt that this technique would be beneficial in the future as a pit and fissure sealant. They used a continuous wave carbon dioxide laser with a 10.6 nanometer wavelength and with energies below 23.5 joules per square centimeter and maximum temperatures at the surface below 1,000 degrees Celsius. They found that the enamel did not crack and that there was very low penetration of a fluorescent die which showed that a tight seal was produced between the tooth enamel and the hydroxyappetite.

Effects on the Pulp

If lasers are ever to be used clinically in every day practice the beams effect on the tooth, soft tissues, pulp, the operator and the patient must be completely analyzed and a adequate level of safety established. Lasers that are found to be clinically effective with a high degree of efficacy will no doubt find widespread acceptance. If using a laser to etch an enamel surface for bonding of an orthodontic attachment the operator must be convinced that the procedure will not damage the pulp.

Lisanti and Zander[47] in 1952 measured the pulp temperature increases in dogs in vivo and the histologic effect of such increases. They did not find any instances of pulp necrosis or death even though temperatures reached 325 degrees Celsius. They did find histologic evidence of pulpal injury which correlated with the amount of heat applied. Histologically they found that the area of insult was walled off and the injured tissue removed followed by replacement of new tissue and eventually secondary dentin.

Zach and Cohen[48] used small thermistors placed right into the pulp chambers and applied a soldering iron at 275 degrees Celsius for various amounts of time to the buccal surface of the monkeys teeth. They found that with an intrapulpal temperature increase of 20 degrees Fahrenheit (11 degrees Celsius), over 60% of the pulps became necrotic and with a 10 degree Fahrenheit rise (5.6 degree Celsius) 15% of the pulps necrosed. Heat below this threshold value produced histologic reactions however the pulp most often recovered.

Nyborg and Brannstrom[49] in 1968 applied 150 degree Celsius heat to human adolescent teeth for 30 seconds and one month later after extraction and histologic examination found that although damage was apparent, healing and new dentin formation had occurred in most of the teeth. DelBalso and Todd[50] looked at protein content and pulpal enzymes of pigs teeth 48 hours after they cut preps in these teeth with a non water cooled high speed hand piece. They saw an increase in the hydrolytic enzymes which they felt represented the denaturization of pulpal proteins and the destruction of the pulp caused by the heat increase. Selzer and Bender[51] concluded in their 1973 study that a temperature rise threshold of 5 degrees Celsius exists beyond which irreversible pulpal necrosis occurs.

Taylor et al.,[52] in 1965 were the first to investigate the pulpal effects of laser irradiation. They applied a laser beam to hamster teeth. Histologic examination revealed severe pulpal necrosis with both acute and chronic inflammatory cells. Most notably, the adjacent teeth were also evaluated and also showed some degeneration. In 1969 Stern et al.,[53] evaluated pulpal response applying lower energy ruby laser irradiation to chimpanzee

teeth in vivo. They found a minimal and reversible pulpal response.

Adrian et al.,[54] in 1971, established energy density thresholds of pulpal response with the ruby laser. Above the threshold limit the most common pulpal change was hemorrhage followed by coagulation necrosis, edema and some inflammatory cell infiltrates. This study did not evaluate the long term effects or whether or not healing occurred. In a follow up study on monkey teeth they compared the pulp effects of a pulsed Nd:YAG laser with a ruby laser.[55] They concluded that the Nd:YAG laser had less effect on the pulp than the ruby laser.

Yamammoto et al.,[56] in 1972, looked at the immediate histologic effects of India ink coated rat teeth irradiated by 8 to 28 Joules of energy from a ruby laser. The ink was placed to help increase the absorption of the laser beam. They found that 28 Joules caused severe but localized pulpal damage however the adjacent teeth were undamaged. They also found slight damage to the cervical gingivae.

Boehm et al.,[57] in 1975, reported on laser heating and its effect on the pulp. He showed that with temperatures of less than 1,000 degrees Celsius and of short duration when applied at the occlusal surface will cause a rise of less than than 5 degrees Celsius in the pulp and thus will not cause permanent pulpal damage. According to his 1977 publication, wavelengths of less than 1.25 micron are reflected more than 40% by dental enamel.[58]

Shoji et al.,[59] in 1985, reported on histologic changes in the pulp after laser pulpotomy using dogs teeth irradiated with either a focused or defocused carbon dioxide laser of various power outputs and irradiation periods. After immediate examination they found the least pulp injury with a

60 watt defocused beam with a 0.5 second duration. They stated that the extent of the pulpal injury appeared to depend more on the total irradiated time than on the output power.

Melcer et al.,[60] in 1985, looked at long term post laser irradiated monkey and dog teeth using the carbon dioxide laser of varying energies. They found a variety of pulp responses with the various powers and concluded that low power carbon dioxide laser irradiation in the order of 3 watts and 1 second exposure causes the formation of secondary dentin under the area lased without causing pulpal necrosis. In a follow up study on monkeys and dogs they looked at the pulp tissue at one day, three days and a six months after irradiation.[61] As before, reparative dentine was formed over time and calcified. Direct radiation of the small iatrogenic pulp exposure actually sealed the wound which healed over time. Sterilization of both the dentin area irradiated and the pulpal area occurred. The exact reaction depended upon the amount of energy applied. A direct energy density application of 1,000 joules per square centimeter lead to partial pulp necrosis followed by healing and pulp survival. Dentinogenesis took place between 800 and 8,000 joules per square centimeter, above which fatal pulpal necrosis occurred. It was thought that the thermal effects caused the stimulation of the odontoblasts however it is possible that the cells were induced by direct laser activation.

Serebro et al.,[62] in 1987, using rat teeth and a carbon dioxide laser with various power outputs and pulse durations tried to determine the threshold limit of power above which results in loss of pulp vitality. They concluded that 0.2 seconds of irradiation is the maximum that should be

used and felt that you should not irradiate a human tooth with a single focused pulse of more than 4 Joules (20 watts for 0.02 seconds). They also felt that the pulsed carbon dioxide laser would most probably cause less pulpal damage at similar amounts of energy than a continuous laser. They concluded that the time of exposure plays a major role in pulpal damage and that using higher intensities but lower duration will cause less damage. It is interesting to note that although the amount of rat tooth enamel was less than half that of human enamel they extrapolated directly from maximum rat tooth energy to maximum human tooth energy.

Launay et al.,[63] in 1987 published the results of a comparative thermal study of the carbon dioxide, Nd:YAG and argon lasers. They used thermography to measure the external heat created (this process uses a computerized video camera with special film) and a pulpal thermocouple to measure internal heat.. With the carbon dioxide laser they found that the external temperature reached the melting point of hydroxyappetite of between 700 and 1,000 degrees Celsius with fluences above 250 joules per square centimeter. At 50 joules per square centimeter they did not measure any pulpal overheating. They defined pulpal overheating as an increase in pulp temperature of greater than 5 degrees Celsius. They concluded that with fluences of under 5,305 joules per square centimeter the pulp would not be permanently damaged. With fluences less than 800 joules per square centimeter they found a rise in pulpal temperature of 0 to 2 degrees Celsius which is under the previously arrived at figure for stimulation of dentinogenesis as a result of laser irradiation. Using the Nd:YAG laser they applied ten impacts at various power settings with energy densities from 190

to 2,228 joules per square centimeter. An initiator was not used and the enamel was not altered. They showed that the Nd:YAG laser energy is transmitted directly through the dental hard tissue to the pulp which would be expected as enamel does not absorb well at the 1.06 micron wavelength. The pulp was overheated and quickly reached dangerous levels. It should be noted that they used the Nd:YAG in the continuous mode. Using the argon laser they applied 20 impacts with energy densities of 318 to 10,287 joules per square centimeter. The results obtained were inconsistent however they did find that irradiation with the argon laser showed no effect on the dental enamel.

In 1989 Shoji and Horiuchi[64] comparing carbon dioxide, argon and Nd:YAG laser application to rat teeth showed that calcified tissue formed in the pulp and that there was an increase in alkaline phosphatase activity in all three laser groups. Powell et al.,[65] in 1989, used dogs teeth that were exposed to a continuous carbon dioxide laser at power densities from 13 to 102 joules per square centimeter. The teeth were evaluated histologically 48 hours later for pulpal response. They found that there was no pulpal damage. Miserendino et al.,[66] in 1989, evaluated the thermal effects of a continuous wave carbon dioxide laser on human teeth in vitro. They concluded that exposure of the tooth should be less than 10 joules and not too exceed 30 joules in order to avoid irreversible pulp damage

Friedman et al.,[67] recently published a study where they looked at the effects of carbon dioxide laser application on pulpal microcirculation as studied in the canine teeth of cats. A laser dopler flowmeter was used to measure the pulpal blood flow before and after laser irradiation. The teeth

were exposed to various energy densitiesand exposure times. They found that the laser caused an immediate transient increase in the pulpal blood flow of 23 to 47%. They concluded that the laser does thermally affect the dental pulp however extensive pulp coagulation does not occur. One must remember that cat enamel and dentin is much thinner than human enamel and dentin.

Powell et al.,[68] in 1990, published a paper concerning safety guidelines for carbon dioxide laser application to teeth. They applied various laser energies to dogs teeth in vivo and then 48 hours later evaluated the teeth histologically. They found that more than 3.5 joules is needed to cause pulpal damage. They also evaluated laser irradiated teeth one month after application and found that when pulpal damage did occur there was healing of the pulp tissues as long as coagulation necrosis did not occur. They also reported on dry pulp temperatures and concluded that an increase of only 6 degrees Fahrenheit occurred with an application of 8 joules of energy. Temperature changes were minimal below 3 joules. The use of the carbon dioxide laser may damage the enamel surface with as little as 5 watts for 0.2 seconds using a 1 millimeter beam and caution should be used.

Laser Etching

Recently more attention has been given to evaluating the possibility of using the laser to etch the enamel and dentin surfaces of teeth in preparation of adhesive bonding. The term laser etching was used to describe the roughened surface that occurred after laser irradiation.

Liberman et al.,[69] in 1984, reported on the use of the carbon dioxide

laser as compared to acid in etching human molars and premolars followed by application of a cylinder shaped composite attachment. A Sharplan carbon dioxide laser with a 12.5 millimeter focal length and a neon-helium focusing beam was used. The experiment consisted of four groups, a non treated control group, an acid etched treated group, a single lased pulse treated group and a continuous pulsed group where the laser beam was moved across the tooth surface by hand. In this study tensile force was measured using an Instron testing device. The non treated control had a mean breaking force of 9 kilograms while the acid etch group broke at a mean of 46 kilograms. The continuous laser pulsed group broke at 27.3 kilograms while the single pulsed group broke at 8 kilograms. They concluded that it may be possible to substitute acid with laser treatment when bonding composite to enamel surfaces. They found that single pulse applications were ineffective. The most effective laser power was a continuous pulse for 2 seconds with a focal distance of 12.5 millimeters a working distance of 0.2 millimeters and energy output of 10 joules with an energy density of 35 joules per square centimeter. Cooper et al.[70] in 1988 looked at the shear strength of composite bonded to laser etched dentin. They found a 300% increase in shear strength as compared to nonlased untreated dentin.

In 1990 Myers[71] reported on a SEM study that looked at Nd:YAG lased enamel surfaces. Using a pulsed Nd:YAG laser at 10 pulses per second at 80 millijoules and a black initiator they found that enamel cratering occurred to a depth of 15 to 40 microns. He concluded that this is a comparable depth effect to the 25 micron depth effect most often seen with

acid etching. They also observed small spherical bodies that represented resolidified surface areas of hydroxyappetite crystals. They did not note any adjacent enamel cracking or fissuring. In a follow up study, Myers and Riddle[72] compared directly acid etched enamel with Nd:YAG lased enamel and found very similar morphologic changes between the two methods. An abstract published by White[73] recently reported on the shear bond strength of Nd:YAG lased dentin surfaces and the results show a significant increase in breaking load as compared to untreated dentin. It was also reported that most of the adhesive fractures occurred at the dentin resin interface.

In 1990 John Hess[74] published a paper on the morphologic changes in enamel following irradiation with the Nd:YAG laser. This SEM study looked at teeth coated with a black energy absorbent laser initiator followed by 30 (95.5 joules per square centimeter) or 75 millijoules (238.8 joules per square centimeter) of laser energy. The wavelength was 1.06 micron with a 150 microsecond pulse length. The laser was applied until all the initiator was removed. Visual examination of the lased enamel showed a well defined opaque surface that was clearly limited to the initiator coated area. The non-coated areas appeared normal. SEM evaluation of the 30 millijoules lased enamel revealed a pockmarked surface with indistinct craters along with bubble like cavities of various dimensions. Very fine surface microcracks were also seen. The 75 millijoules surface showed very distinct disc shaped craters with overlapping. The craters were around 230 to 250 micron in diameter. The crater centers were flattened and filled with low smooth ridges and depressions with many small bubble like openings of various dimensions and many pores. The edge of each crater showed a rim

of bubbled and mounded solidified enamel. The areas in between craters and at the edge of the etched area showed a smooth surface with small circular cavities or pores and a spattering of enamel from the nearby impact craters. It was noted that the energy levels used were well below those levels that would cause pulpal necrosis. One advantage of this technique appears to be the ability to limit the etched surface by applying initiator to the specific area to be etched, the process is also rapid and accurate. He concluded that the surface characteristics were very amenable to composite bonding.

In a follow up study, Hess[75] compared the bond strengths of laser and acid etched enamel. Comparison was made between extracted human acid etched and bonded teeth with Nd:YAG lased (75 millijoules at 15 pulses per second) and bonded teeth using an Instron testing device in the shear mode. A comparison was also made between both gel and liquid etch. It was found that the liquid etched surface had a significantly greater bond strength than either the gel or lased treated surfaces. The laser treated surface was found to have a lower but comparable bond strength to the of the gel etched surface. Thus it was concluded that perhaps laser etching may be used in preparing teeth for bonding of orthodontic brackets.

White et al., recently reported on shear bond strength of Nd:YAG laser etched enamel of human extracted teeth after placement of an initiator. The laser settings were varied from 0.3 to 3.0 watts at 10 to 20 hertz and 30 to 150 millijoules per pulse. Standard mesh backed metal brackets were bonded with a no mix adhesive, loaded with 400 grams for ten minutes and stored at 100% humidity for five days. An Instron device was used to test the

shear bond strength at a crosshead speed of 5 millimeters per minute. They found a maximum bond strength at 150 millijoules per pulse at 20 hertz. No comparison to acid etching was made.

Bovine Teeth as a Substitute

In the past, bond strength studies have been conducted using extracted human teeth. With extracted human teeth becoming increasing difficult to obtain, especially in the large numbers needed to conduct bond strength studies, increasing numbers of researchers are turning to bovine teeth as a substitute. In a computer literature review using the Medline reference search system, this investigator found over ninty published papers in the recent literature that used bovine teeth as a substitute for human teeth. In 1964, Glimcher et al.,[77] reported on the amino acid composition of the enamel proteins of erupted bovine teeth. They described the existence of a calcified collagen layer that is continuous with the cementum. This layer may also be covered with additional proteins from the saliva and oral cavity. The protein content of erupted bovine enamel was found to be 0.06%.

Brauer and Termini[78] in 1972 and Otsuki and Takeuchi[79] in 1976 evaluated tensile bond strength to acid treated bovine enamel. Johnson et al.,[80] in 1976, used 210 bovine teeth to compare shear bond strengths using seven different adhesives and found a wide range of breaking values ranging from three to thirty two pounds. Spitzer and Bosch[81] in 1975 compared the absorption and scattering of light in bovine and human dental enamel. Measuring thin slabs of both bovine and human enamel at wavelengths between 220 and 700 nanometers, they found that the common 270 nanometer absorption peak was three times as high in the

bovine enamel as human enamel. They concluded that this was mainly due to a higher content of an organic component. Besides this, they found no substantial difference between refractive indices of human and bovine enamel.

In 1980, Borggreven et al.,[82] looked at the effects of laser irradiation on the permeability of bovine dental enamel. Using a carbon dioxide laser at an energy level of 10 joules per square centimeter they found and increase in the transport of ionic and non-ionic compounds increased after laser irradiation. This is different from results of previous experiments where a decreased permeability was found and used to explain the increased resistance of enamel to surface demineralization. An abstract by White et al.,[83] concluded that Nd;YAG laser application does not sufficiently alter the hydraulic conductance of dentin. In 1983, Nakamichi et al.,[84] published their paper on using bovine teeth as a substitute for human teeth in adhesion bond strength tests. They found that there was no significant difference between human and bovine teeth however the mean values were always slightly lower with the bovine teeth. Scanning electron microscopic evaluation on unetched samples revealed even surfaces with some scratch lines that were produced by the polishing process. They found that the bovine enamel appeared slightly rougher. Etched human enamel surfaces revealed an arcade shaped prism structure while the bovine enamel had a smaller oval shape. Previous anatomical and histochemical studies have shown that all mammalian teeth are similar in structure and composition.[85,86]

Yu and Chang[87] in 1966 evaluated the critical surface tension of bovine and human teeth and found that it was lower in bovine teeth resulting

in slightly lower adhesive strength. Moriwaki et al.,[88] in 1968 reported that compared with human enamel, bovine enamel had larger crystal grains and more lattice defects. They felt this was due to the fact that bovine teeth developed more rapidly than human teeth both before and after eruption. Whittaker et al.,[89] in 1983 reported that prism dimensions, prism arrangement and the width of the interprismatic zone was different in bovine enamel as compared to human enamel. Gantt et al.,[90] in 1985 using microdissection, reported a marked crossing of prisms in the inner third, narrower prisms, thicker and longer crystallites and a more porous surface in bovine enamel as compared to human enamel.

Edmunds et al.,[91] in 1988 compared artificially produced carious lesions in human, bovine, equine and ovine enamel and found that although there were differences in the depth of the carious penetration, the bovine enamel was very similar to that of human enamel. In a recent study, Ruse et al.,[92] evaluated the composition of bovine enamel and concluded that there is a 12 micron thick organic rich layer on the surface that needs to be removed prior to adhesive bond testing.

The intention of the present study was to answer the following questions.Can the laser be used for etching enamel surfaces prior to orthodontic attachment with a high degree of efficacy? And does laser etching provide any advantages over conventional acid etching techniques?

STATEMENT OF THESIS

The purpose of this experiment was to compare the bond strengths achieved using laser etching, acid etching and no etching. Evaluation of the surface characteristics of the laser etched, acid etched and non etched surfaces was made using a SEM. The debonded bracket and enamel surfaces were evaluated using a light microscope to determine the plane of fracture. Two different types of lasers were used, the Nd:YAG laser and the carbon dioxide laser. The hypothesis made is that the laser etched enamel surface will show a similar shear bond strength as compared to the acid etched surfaces. It was also hypothesized that the surface characteristics of the laser and acid etched enamel would be similar.

METHODS AND MATERIALS

Materials

A total of 71 bovine incisors were freshly extracted at a local slaughterhouse. The roots were sectioned from the crown 25 millimeters from the incisal edge using a separating disc on a low speed hand piece and stored in distilled water. Bovine teeth have been found to be a good substitute for human teeth and the bovine incisor has a broad flat surface for consistent reproducible bonding. The crown segments were tacked flat to a glass surface with a small drop of cyanoacylate cement (super glue) and a 32 millimeter diameter plastic pipe 19 millimeter in height was placed over the immobilized tooth segment. The inner surface of the plastic pipe was lightly coated with Vaseline to facilitate removal of the acrylic block. Type II autocure acrylic (COE-LOR R.C.T., Coe Laboratories Inc., 3737 West 127 Street, Chicago, Il 60658) was mixed according to the manufacturers instructions and poured over each crown. After polymerization was complete the circular acrylic block was gently tapped out of the mold.

A uniform flat enamel surface was obtained by sanding the specimens with progressively fine silicon paper. One hundred eighty grit silicon sandpaper was first used to expose a small spot of enamel followed by 30 second applications of 240, 320, and 400 grit silicon sandpaper. The final enamel surface was obtained by sanding for 60 seconds with 600 grit silicon carbide paper after which the enamel surface was microscopically evaluated to ensure a uniform smooth surface devoid of scratches. Any

specimens that showed areas of exposed dentine or any remaining organic material were eliminated. The 71 samples were divided into four groups (Table 1).

The first group consisted of 21 teeth that were etched with 37% phosphoric acid in liquid form. The area of enamel to be etched was first dried completely with oil and moisture free compressed air. After etching the surface was rinsed with distilled water for sixty seconds and again dried for sixty seconds with moisture and oil free compressed air. A thin layer of sealant (Reliance Phase II sealant resin part A and B) was applied to each specimen and moisture and oil free compressed air was applied for ten seconds to obtain a uniform film thickness as per the manufacturers instructions. A two paste composite resin (Reliance Orthodontic Products Inc., PO box 678, Itasca, Il 60143) was mixed in a 1:1 ratio and applied to the bracket base. The bracket was then placed onto the enamel surface and seated with a dental surveyor to provide a constant 4.4 lbs of force for two minutes. Reliance phase II orthodontic adhesive system is one of the most commonly used bonding adhesives and provides exceptional bond strength. Any composite flash was removed before polymerization with a dental explorer. Each specimen was allowed to bench cure for an additional ten minutes. In order to simulate the oral environment test specimens were stored for 24 to 36 hours hours in distilled water before testing. The back of each specimen was randomly labeled by an independent operator to ensure that there was no bias during testing. This was also done with the two other experimental groups and with the untreated control group and the master list was sealed in a manilla envelope until the results were analyzed. The metal

brackets used in all the groups were 0.022 slot, wide, standard edgewise central incisor brackets with a flat base (Ormco Corp., Glendora, CA 91740) with 100 fine mesh backing was used because it provides excellent mechanical retention.[93, 94]

The second experimental group consisted of twenty specimens that were etched using a Nd:YAG laser. The teeth were first dried using moisture and oil free compressed air then a thin layer of laser initiator (Black Sumi ink KF2, Yasutomo and Co., San Francisco, CA) was applied to the enamel surface. Compressed air was applied to the ink painted enamel to obtain a uniformly coated surface. The area was lased using a 320 micron contact fiber at a power setting of 15 pulses per second and at 75 millijoules as recommended by the Institute for Laser Dentistry (1991) until vaporization of the initiator was complete. Sealant was applied to the enamel surface and a bracket bonded using the same procedure as the first acid etched group. Test specimens were stored for 24 to 36 hours in distilled water before testing.

The third group consisting of eighteen samples was prepared identically to the previous group and was then etched with a carbon dioxide laser at 7 watts in mode 5 (0.01 second exposure time with a repetition rate of 10 pulses per second and a duty cycle of 10 percent). This setting was recommended by Tessendorf[95], and Dederich.[96] Sealant was placed followed by bonding of an orthodontic bracket and stored 24 to 36 hours in distilled water.

The fourth or control group consisted of twelve samples which received no etching preparation. All procedures were followed exactly as

were performed on the previous groups except for the etching procedure.

How Lasers Work

Application of laser energy involves the processes of absorption, stimulated emission and spontaneous emission. Absorption is when an atom in a lower energy level is raised up to a higher energy level after exposure to an energy source. Stimulated emission occurs when an atom that is already in an excited state decays to a stable state after it interacts with a photon that exactly corresponds to the absorption energy. Spontaneous emission occurs when an atom that is already in a higher energy state decays to a more stable state thus releasing a photon.[97]

The laser beam has three features. First, it is monochromatic. Light is emitted at a single wavelength which has a very narrow line width, therefore the radiation waves all have the same frequency and energy. This property is very important because it provides the high spectral power density of the laser beam. the second feature of the laser beam is that it is highly collimated. There is almost no divergence of the photons and all the emitted waves are almost parallel. This property is important because it allows for excellent transmission through a delivery system such as fiber optics. Finally, the laser beam is coherent. The complete wavefront is in perfect harmony with the rest of the laser beam both in a longitudinal and lateral dimension. Thus all the waves are in a particular phase relationship to each other both in time and space.

Most lasers have three common components, a population inversion, an active medium and an optical resonator. The population inversion is a pumping mechanism that stimulates and amplifies the active medium. It

usually consists of radiation from an electrical discharge, a high injection current or a flashlamp. The active medium is the light source and can consist of molecules or atoms in the liquid, solid, or gaseous form. The external radiation source stimulates the atoms of the active medium to jump to a higher energy state creating a population inversion. Thus most of the atoms have been converted to a different energy level and thus the term population inversion. The name of the laser is based on the active medium, e.g., carbon dioxide, Neodynium, Argon, helium-neon. Two very highly polished mirrors are placed at both ends of the laser cavity, together they comprise the optical resonator system. The resonator system amplifies the beam and produces a coherent, collimated, narrow beam. One of the mirrors is reflective while the other is partially transmissive. The laser medium is placed in the optical cavity and when activated (pumped), specific wavelength photons are emitted. Photons bounce off the fully reflective mirror and some pass through the partially transmitting mirror. After being focused by a focusing lens the photons form a highly collimated, monochromatic and highly directional laser beam. The optical resonator further amplifies the process and after a certain amount of time a steady energy state is created and the additional energy produces the laser beam.

Most lasers have their power supply, optical components, mechanical shutter and electronics contained in a single instrument with a control panel. The control panel may include an on-off switch, power level switch, exposure duration switch, pulsed or continuous wave switch, pulse frequency switch, and some wavelength adjustment switches. Some pulsed lasers produce high peak energies however the average energy is usually

much lower. Often the laser energy is transported to the operating field by fiber optics that are available in various sizes. Smaller fibers are now being developed which will enable the laser beam to be applied more accurately. Transmission of the beam can also be accomplished using optical mirrors.

The distinguishing characteristic of lasers is the wavelength, which is directly related to the laser medium. The different wavelengths can be devided into three subgroups. The ultraviolet spectrum ranges from between 140 to 400 nanometers. The visible spectrum ranges from between 400 to 700 nanometers. The infrared spectrum ranges from 700 nanometers up to the microwave spectrum. Also very important is the excitation mode which can be either continuous or pulsed.

The interaction of the laser beam photons on living tissue is very complicated and produces various reactions, all of which are as yet not completely understood. The effect of the photons on the tissue depends on the tissue itself, its density, surface characteristics, composition and structure as well as on the wavelength, pulse duration, and energy density of the laser beam. Three types of interactions have been investigated. They are photochemical interactions, thermal interactions and nonlinear processes. The photochemical effect occurs when laser light is directly absorbed without any thermal effect which leads to a change in the chemical and physical properties of the tissues molecules and atoms. Thermal effects occur when tissue is vaporized which is caused by the absorption of the photons. This leads to an increase in the tissues internal lattice vibrations which after conversion into thermal energy destroys the tissue. Non-linear effects include both photodisruption and photoablation. Photodisruption

occurs when high energy short pulsed photons actually ionize the tissue. This occurs by the building up of a plasma which causes a high pressure explosion completely destroying the tissue. Photoablation is when high energy photons break up a molecule directly causing electron dissociation. Excimer lasers have high energy photons that can cause such a process and if a carbon dioxide laser is set at a very short pulse duration photoablation can also occur. It takes a specific amount of energy to break molecular bonds.[98]

The depth of penetration of a laser beam can be controlled by changing the wattage, the focal length of the laser beam or the time setting. The cross sectional area of the laser beam can be changed by changing the focal length. The laser beam passes through a lens and converges to a focal point and from there it diverges At the focal point the beam is the narrowest and the cross sectional area is the smallest. The cross sectional area increases and the strength of the beam decreases as you get further away from the focal point and out of focus with the beam. As the beam diverges from the focal spot and as the power of those photons diminishes, the underlying tissue is protected. Thus, the operator can vary the distance from the mirror or fibre optic device to vary the amount of energy delivered to the tissue surface. One can also vary the total amount of energy delivered by changing the amount of time that the tissue is exposed to the laser beam. Exposure time can be varied by using the laser in a continuous, pulsed or single emission mode. The pulse duration can also be increased or decreased. Other methods of controlling thermal build up are the use of a water or air cooling system.

Lasers

The Nd:YAG laser manufactured by American Dental Lasers and the carbon dioxide laser manufactured by Luxar Corporation were used in this study. Both lasers are commercially available and are being marketed specifically to the dental profession. They are both approved by the FDA for use on oral soft tissues and both have applied for approval on dental hard tissue. These lasers were chosen because they are readily available and are being used clinically in the dental field for both hard and soft tissue applications.

Safety Procedures

When using a laser one must be careful not to view the beam directly. This may be hazardous and cause irreversible damage to the eye. Viewing the deflected light will not generally cause retinal damage. The most common retinal injury that may result is a reduced field of vision. With higher exposures permanent damage may occur. If the fovea in the retina is affected there may be an effect on central vision. It is recommended that the appropriate eye protection be worn at all times when using the laser. One must consider the nominal ocular hazard distance which is the range at which the laser power per unit area of the beam comes below the maximum allowable level. Because there is not much divergence of a laser beam the effective distance can be great. If the beam is delivered via a fibre optic system it may emerge from the fibre at a divergence of approximately 17 degrees. This divergence makes the ocular hazard distance very short. When deciding on eye protection consideration must be given to the wavelength of the emitted beam. If the appropriate material is not used even

more damage can occur depending on the properties of the material. It has been reported that the material used in the fabrication of the protective eye glasses may cause focusing of the beam.[99] During the experiment proper eye protection was worn by the operator at all times.

Procedures to Test Bond Strength

Shear bond strength was determined using an Instron universal testing machine model number 1125 with an error rate of plus or minus 0.5 percent of indicated load or plus or minus 0.25% of the range of use whichever is greater. A 100 pound range was used of the 1,000 pound load scale. A crosshead speed of 0.05 centimeter per minute was used. This is a common crosshead speed used for shear bond strength testing. A custom designed stainless holding device secured the specimens in distilled water at room temperature during testing. A 0.47 millimeter thick metal spacer was placed between the enamel surface and the shear rod to make sure that the shear rod contacted the bracket base of every specimen at the same spot. The brackets were turned sideways to obtain better contact with the shear rods without bending of the tie wings. The shear rod was positioned by eye parallel to the bracket surface so that the best approximation of uniform contact with the shear rod surface to the bracket was achieved. The Instron unit was calibrated so that consistent loads could be administered. Breaking loads were recorded on a strip chart recorder using pounds as the unit of measurement. Since all the brackets used were similar, breaking load results were used directly without regard to the surface area of the bracket.

Light Microscope Photography

A Wild light microscope (model number M5 52552) with an attached 35 millimeter camera was used to examine the site of bracket failure. Photographs of both the enamel and the bracket surfaces were taken of all samples. A 100 ASA setting and bracketed f stops were used. The interface where fracture of the bracket occurred was recorded and evaluated. The surfaces were observed at magnifications of 12X and 25X.

SEM Procedures

Six additional bovine incisors were sectioned at the root in like fashion as those being used in the shear bond testing, however they were not imbedded in acrylic. A separating disc was used to scribe a cross on the flat surface after smoothing with the sequence of silicon sand papers. Four quadrants were thus formed. The quadrants were divided and tested in the following format, control, acid etching, carbon dioxide laser etching, and Nd:YAG laser etching. The teeth were then vacuum dried in a high vacuum for 48 hours. The teeth were mounted on SEM stubs in a manner that presented the treated surfaces for examination. The samples were then gold sputtered using a BIO RAD SEM coating system unit at 2.4 KV and a vacuum of 1 X 10^{-3} millimeters of mercury. A 15 nanometer thick gold coating was applied. This thickness was used because it reduces charging of the sample while still providing excellent detail at the low magnifications that were used to evaluate the surface characteristics of the enamel. The samples were evaluated using a JEOL 35CF model SEM at 25 KV and comparative photographs of four areas were taken at various magnifications. Polaroid 55 positive/negative 4 x 5 inch black and white professional instant

sheet film was used. The photographs were compared for surface changes.

Statistical Analysis

The shear bond strength was statistically evaluated for differences between groups using the student t test. Means, standard deviations and variances were calculated and compared. All data was evaluated at the 95% confidence interval (alpha = 0.05).

RESULTS

Bond Strength

Results from the Instron shear strength test (see Tables 1,2) indicate that the acid etched group had a mean bond strength of 65.4 pounds (S.D.=13.4 pounds). This was significantly greater than that achieved with the Nd:YAG laser ($p< 0.001$) and the carbon dioxide laser ($p< 0.001$). The mean bond strength of 17.9 pounds (S.D.= 5.4 pounds) achieved with the Nd:YAG laser was significantly greater than the 11.8 pounds (S.D.=5.6 pounds) achieved with the carbon dioxide laser ($p< 0.002$). The non-etched group had a mean bond strength of only 2.2 pounds (S.D. = 2.1 pounds) which was significantly less than the other groups.

SEM Evaluation

Evaluation under the SEM revealed different surface characteristics for the four different groups. The non etched control group revealed a consistently scratched surface with grooves running parallel and a collection of debris in some of the grooves (see Figures 1A,1B). The acid etched surface showed a roughened uniform appearance with no evidence of the scratches and grooves seen on the controls (see Figure 2A). In most areas the acid etch patern showed projections of more resistant enamel rods, with the deeper etch occurring in the interrod areas around these projections (see Figure 2B).

The Nd:YAG laser treated surface showed a variety of changes

compared to the control. In Figure 3A, relatively smooth areas with shallow scratches or grooves are intermixed with some areas that were much rougher. These rougher circular craters had what has been described as a burst bubble appearance. At higher magnifications of the smoother areas, fine pores were resolved with diameters ranging from approximately 0.5 to 1.6 microns. There also appeared to be an increase in the number of micro cracks (see Figure 3B).

The carbon dioxide laser etched surface mostly showed areas of uniform grooves similar to the unetched control area, however the grooves were slightly reduced and the surface had a lighter glazed like appearance (see Figure 4A). There appeared to be a large amount of debris on the surface as compared with any of the other groups (see Figure 4B). Occassionally, areas of the carbon dioxide treated enamel did show irregular appearing craters with a raised rim. In these areas the craters were very well formed and appeared to be rather deep. The craters can best be described as concentric uniform raised rim objects with an area of solidified debris strewn around the outside of the raised rim. The diameter of the crater was found to range from 5 to 15 microns.

A low magnification SEM photograph shows the entire labial surface of one of the samples comparing all four groups on one tooth (see Figure 5A). In this photograph one can readily see the difference between the four groups. The non etched control seen in the lower left hand corner shows a uniform or smooth appearance. The acid etched area in the lower right hand corner reveals a very light surface. The higher magnifications revealed that this light appearance was due to the increased secondary

electrons being deflected from the enamel rod projections (see Figure 2B). The Nd:YAG etched area appears in the upper left hand corner and reveals a series of large irregular crater like depressions surrounded by lighter regions where pores and debris were seen at higher magnification (see Figure 3B). The upper right hand corner reveals the carbon dioxide lased surface with a more uniform appearance than the Nd:YAG treated surface. However, the slightly lighter surface indicates some changes occurred to the enamel in comparison with the control. Some large craters can be seen especially at the junction of the carbon dioxide lased area with that of the acid etched area. A close up of this area is shown in Figure 5B. This is an area where a groove was cut in the surface to delineate the various sample areas. This area also came in contact with the acid etch solution which pooled in the groove. Figure 5B reveals the etched enamel rods along their long axis.

During the desiccation process many cracks appeared throughout the samples. This was due to the large size of the sample and the fact that the whole crown was used and not just the labial section. The desiccation process took 48 hours and difficulty occurred obtaining the necessary vacuum. Thus the amount of cracking caused by the laser treatment itself verses that caused by the drying in sample preparation was difficult to accurately analyze.

Light Microscope Evaluation

Light microscopic inspection of the enamel surface and bracket bases after Instron debonding revealed that the acid etched surface failed almost exclusively at the bracket/composite interface (see Figures 6A,6B). The

composite material remained for the most part on the enamel surface and mirrored an impression of the debonded bracket base. The imprint of the mesh metal base glistened under the light microscope. Finger like projections of composite remained on the mesh pad. In some instances up to one third of the composite remained on the pad. The remaining composite occurred on the end of the bracket away from the Instron force application point.

The laser etched samples and the non etched control group fractured almost exclusively at the composite/tooth interface (see Figures 7A,7B,8A,8B,9A,9B). The composite material remained for the most part on the bracket mesh and had a dull appearance. In a few of the Nd:YAG lased samples small amounts of composite did remain on the tooth surface usually in a random pattern.

Table 1.--Bond Strength Comparisons in Pounds

ETCH TYPE	SAMPLE SIZE	MEAN	S.D.
ACID	21	65.4	13.4
ND:YAG	20	17.9	5.4
CO_2	18	11.8	5.6
NO ETCH	12	2.2	2.1

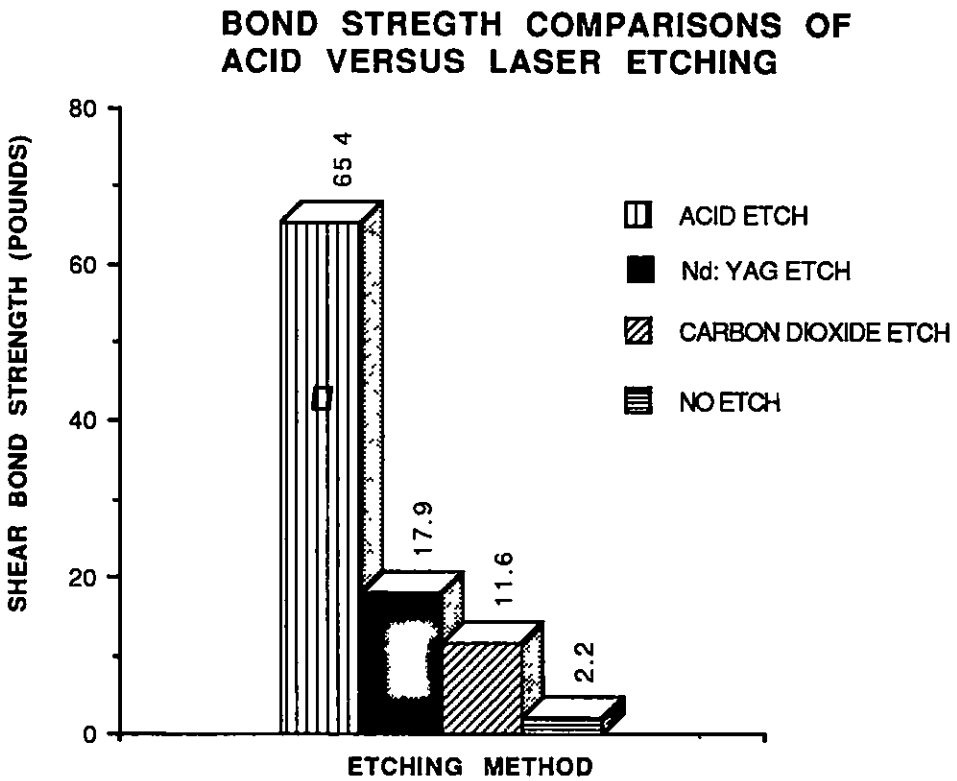
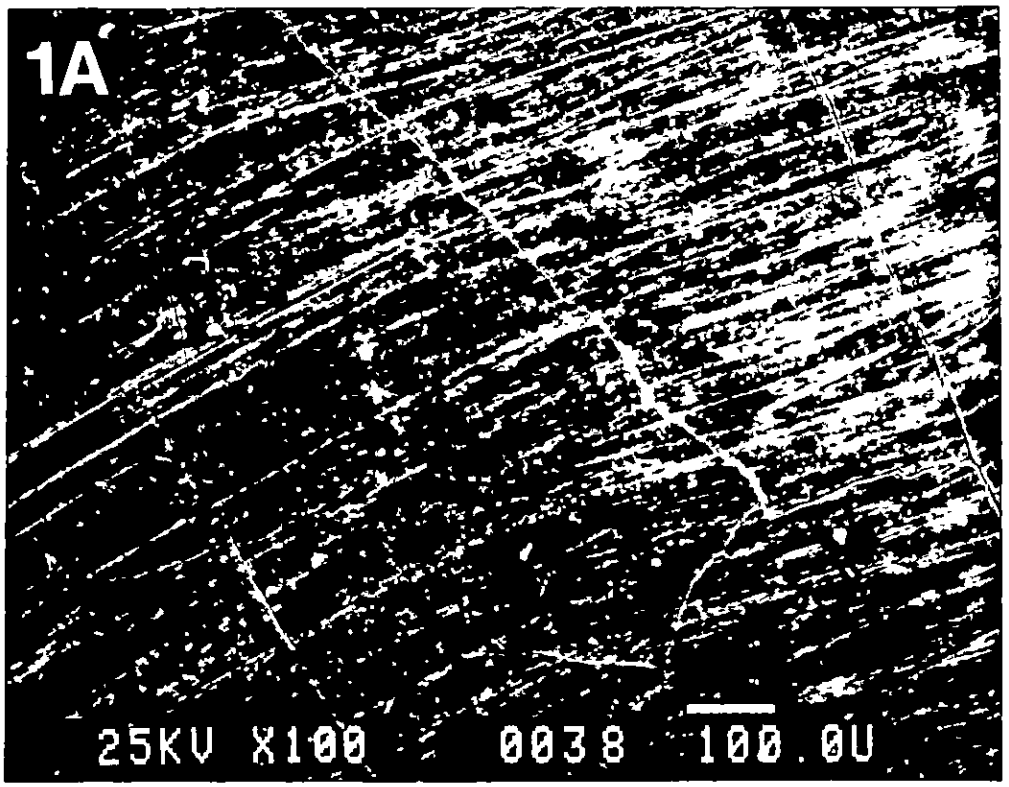


TABLE 2.-- GRAPH: Bond strength comparisons of acid versus Nd:YAG, carbon dioxide lasers, and non etched control. ($p < 0.002$)

Figure 1a. SEM of non etched surface at 100 X magnification

Figure 1b. SEM of non etched surface at 1000 X magnification


1A
25KV X100 0038 100.0U

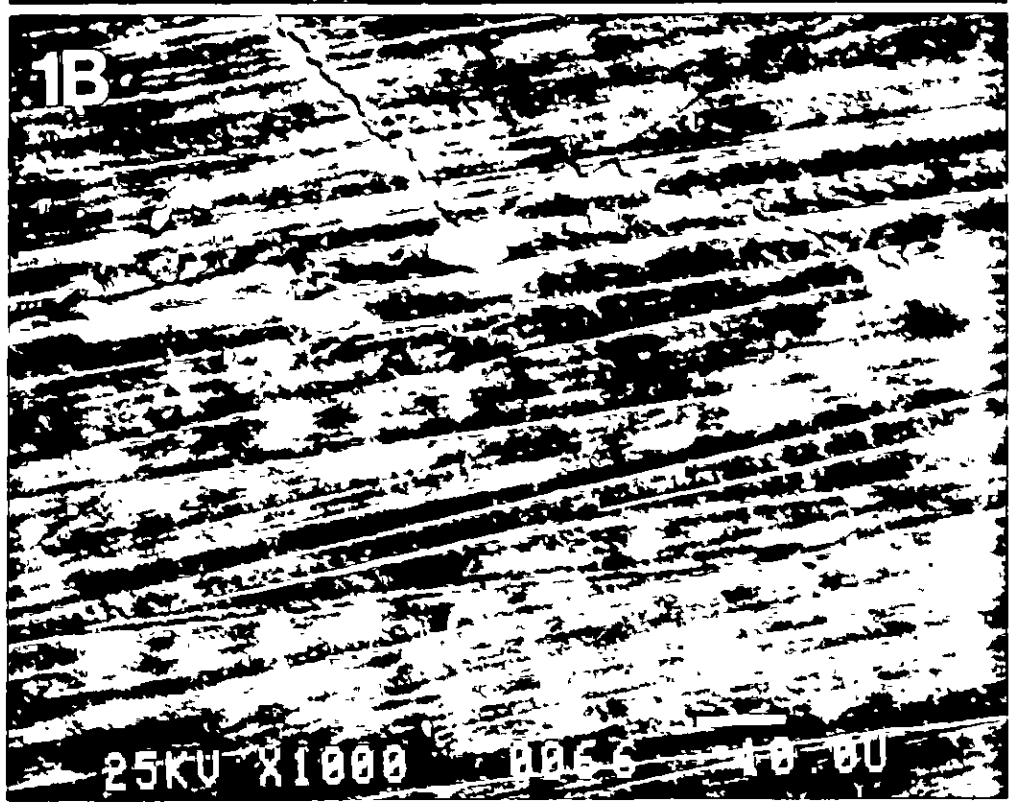

1B
25KV X1000

Figure 2a. SEM of acid etched enamel surface at 100 X magnification

Figure 2b. SEM of acid etched enamel surface at 1000 X magnification

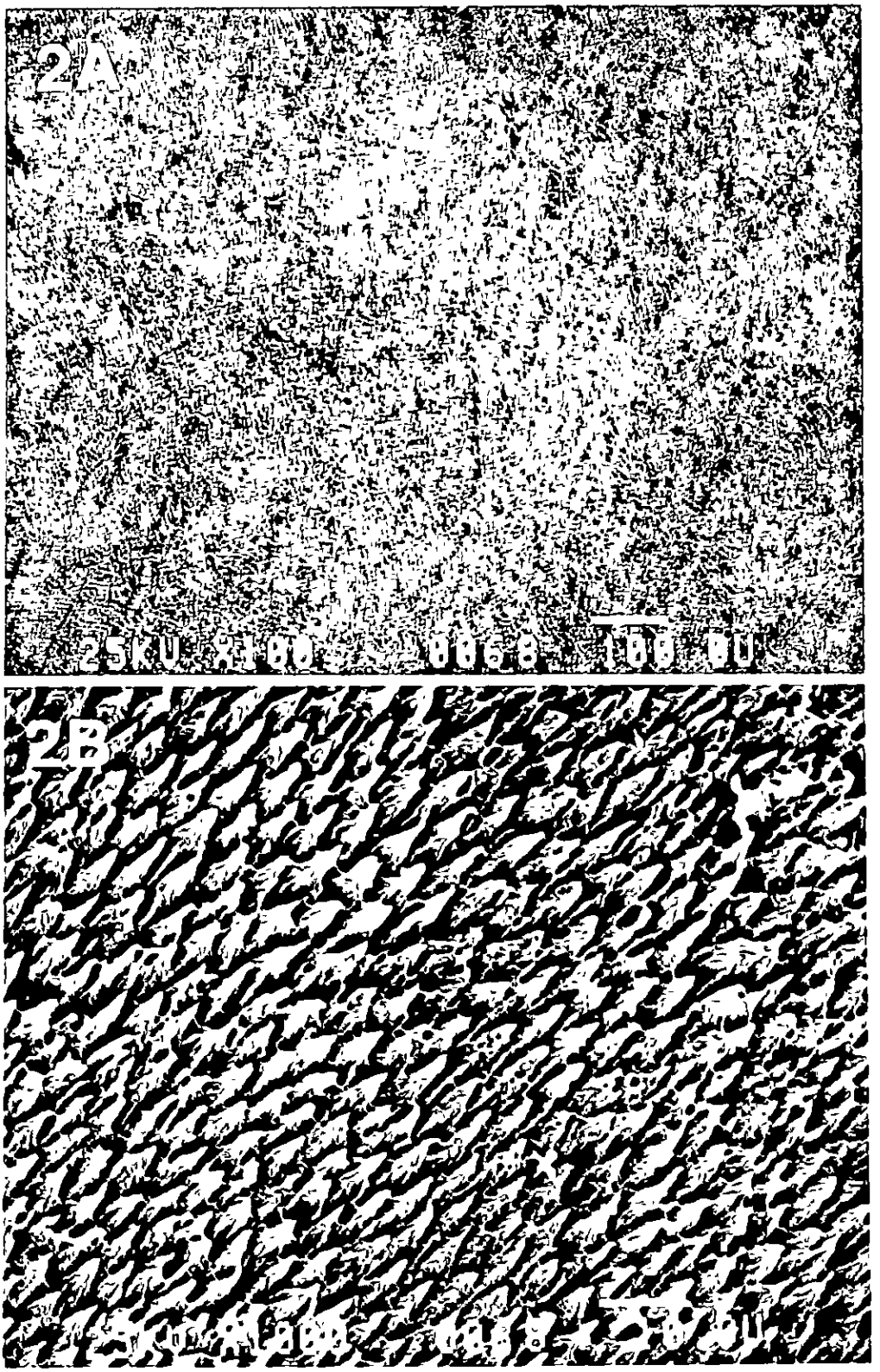

2A
2B

Figure 3a. SEM of Nd:YAG laser etched enamel surface at 100 X magnification

Figure 3b. SEM of Nd:YAG laser etched enamel surface at 1000 X magnification


3A
25KV X100

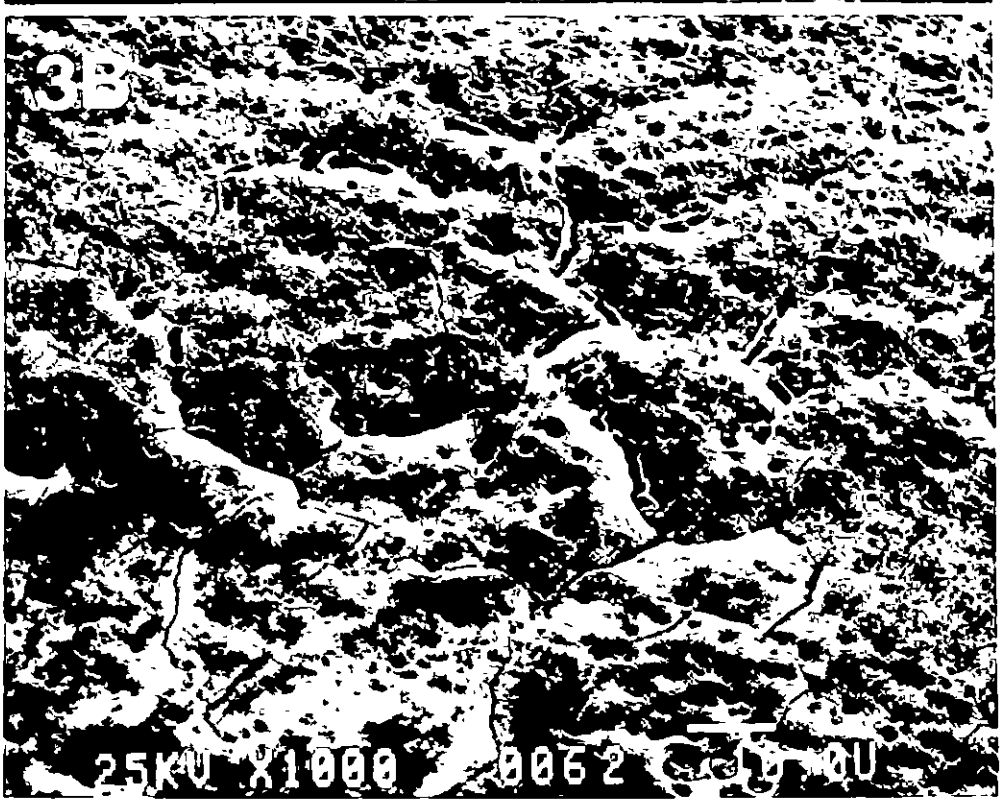

3B
25KV X1000

Figure 4a. SEM of carbon dioxide laser etched enamel surface at 100 X magnification

Figure 4b. SEM of carbon dioxide laser etched enamel surface at 1000 X magnification

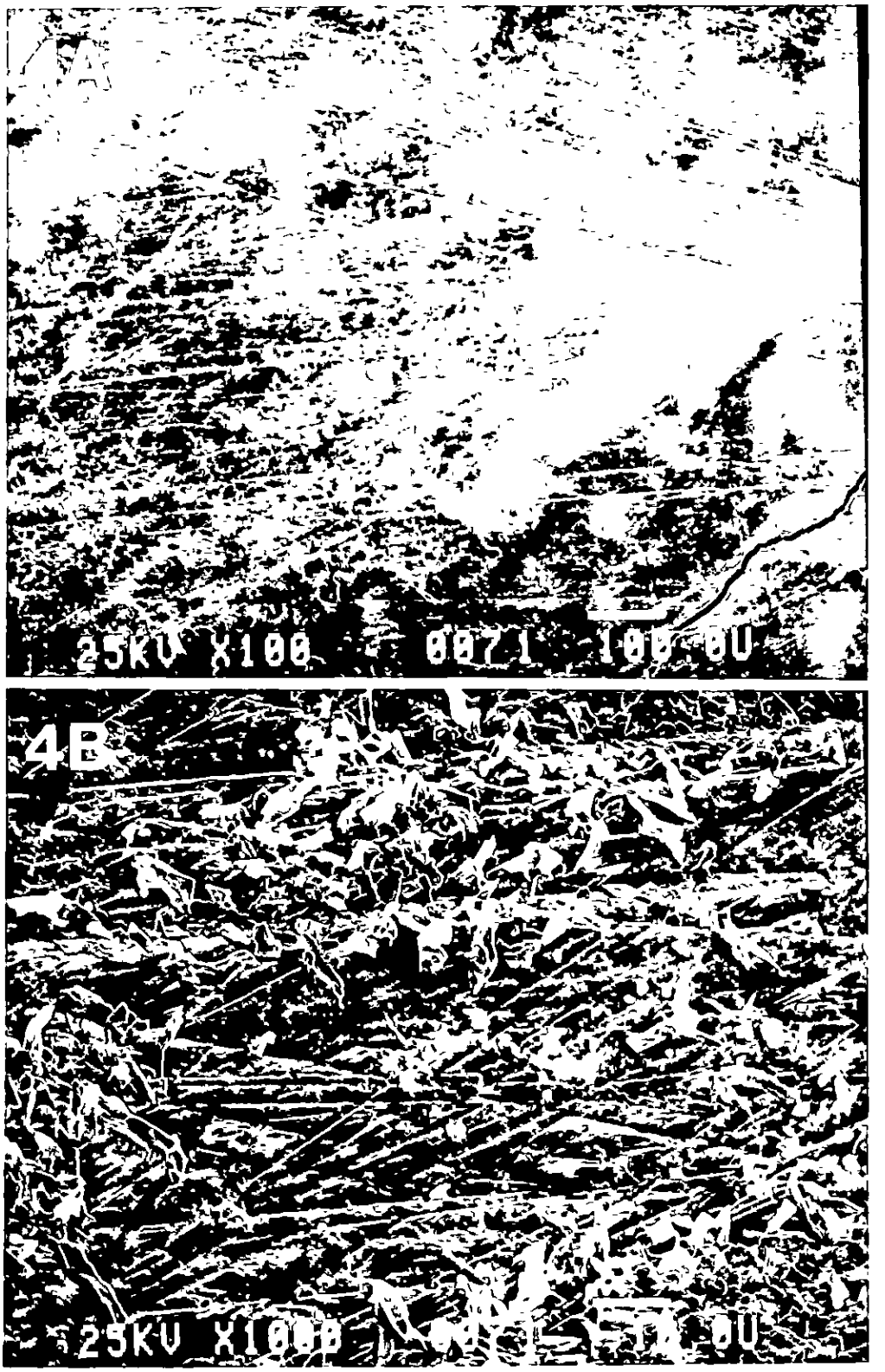
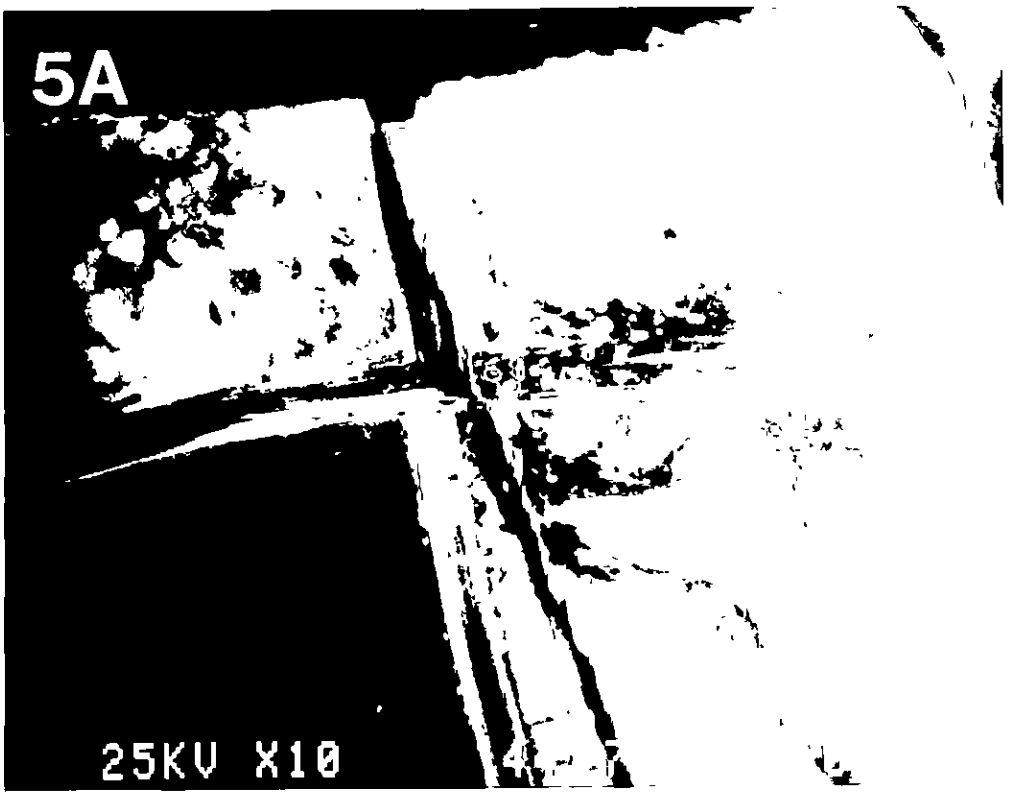

25KV X100
4B
25KV X100

Figure 5a. SEM of entire enamel surface at 10 X magnification

Figure 5b. SEM of groove cut surface at 200 X magnification


5A
25KV X10


5B
X200

Figure 6a. Photograph of debonded enamel surface of acid etched sample at 12 X magnification

Figure 6b. Photograph of debonded bracket surface of acid etch sample at 20 X magnification

Figure 7a. Photograph of debonded enamel surface of Nd:YAG laser etched sample at 12 X magnification

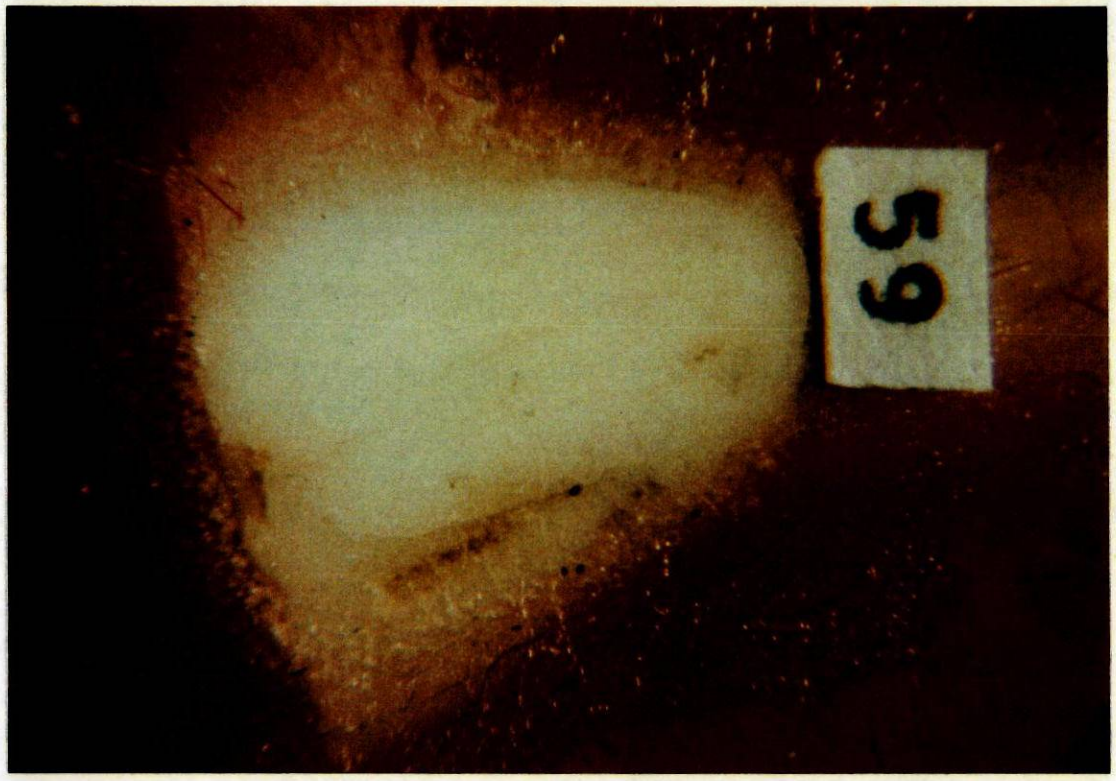
Figure 7b. Photograph of debonded bracket surface of Nd:YAG laser etched sample at 20 X magnification

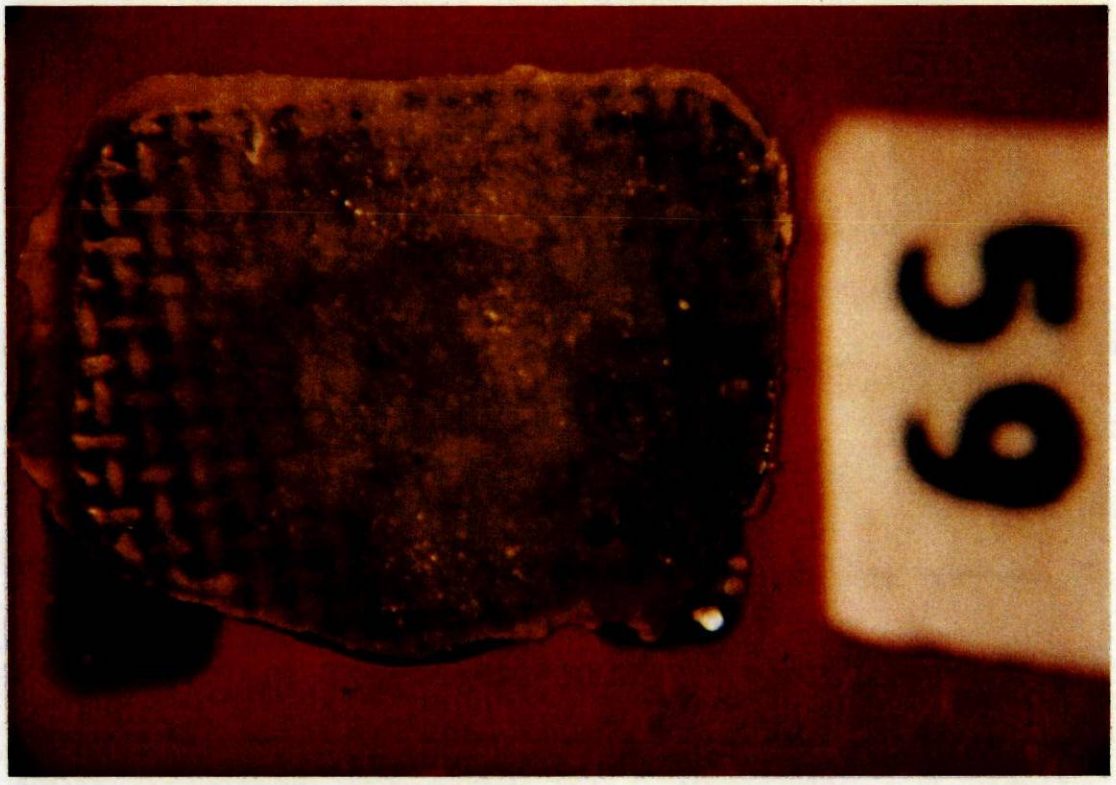
6B

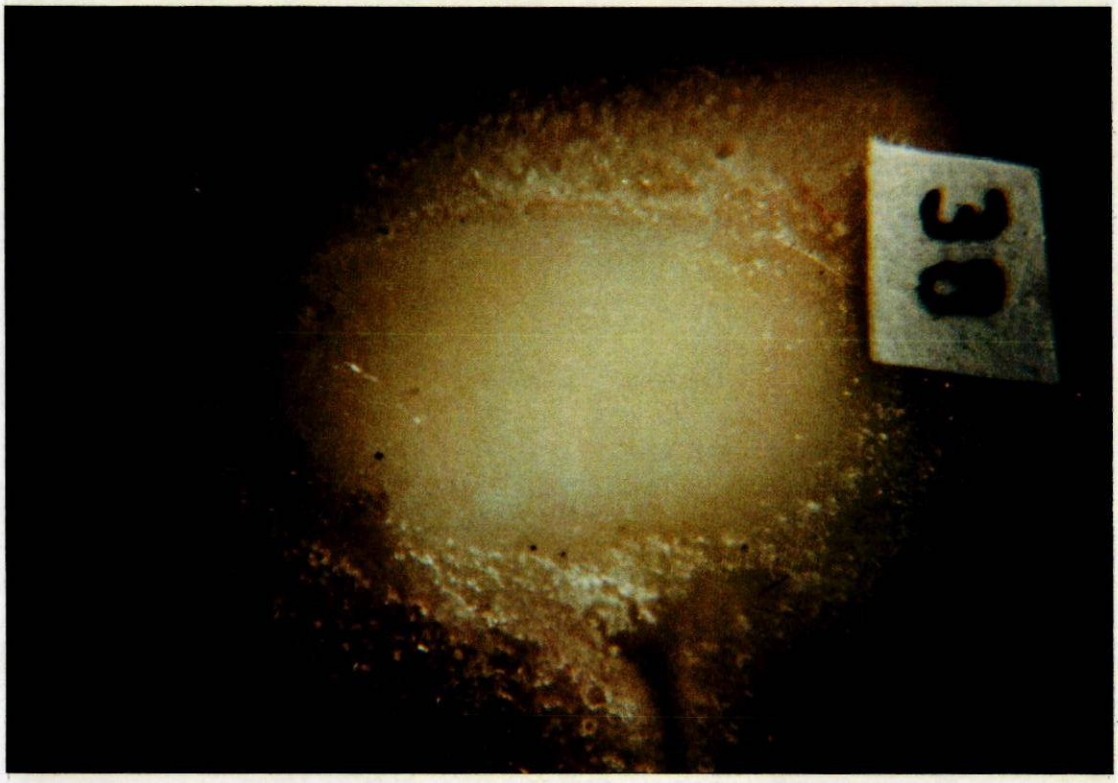
6A

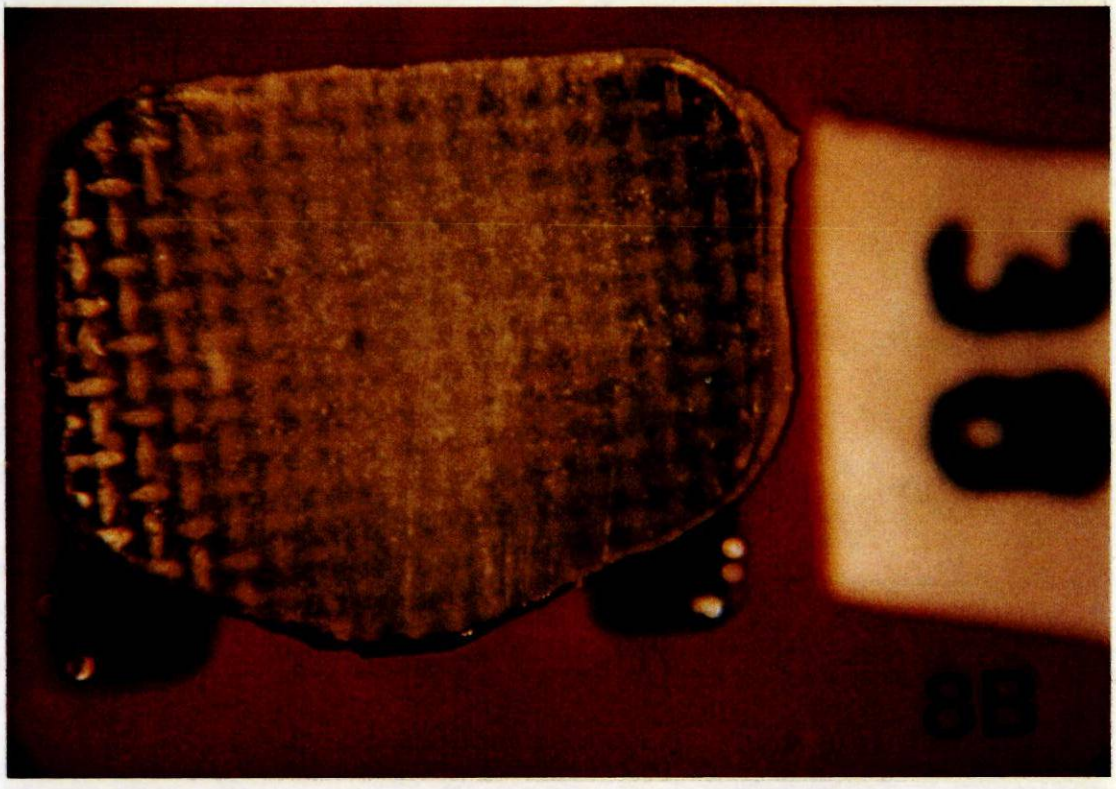
Figure 8a. Photograph of debonded enamel surface of carbon dioxide laser etched sample at 12 X magnification

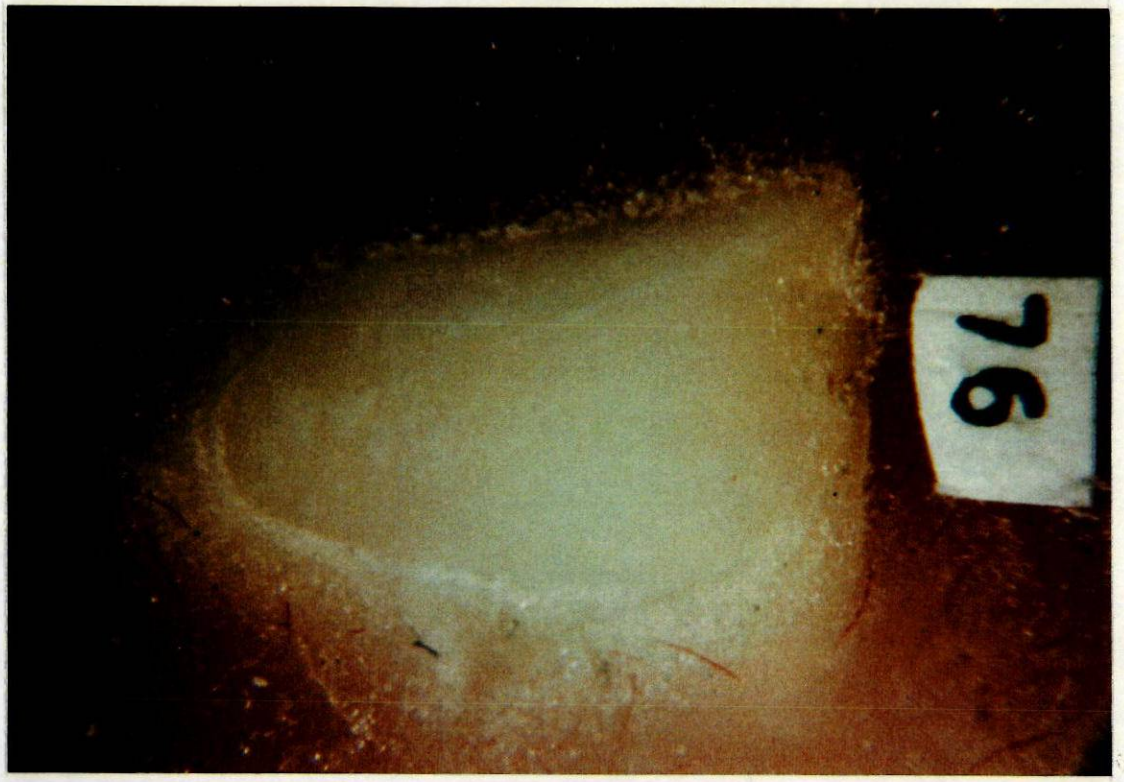
Figure 8b. Photograph of debonded bracket surface of carbon dioxide laser etched sample at 20 X magnification


59


59


86


86
8B


76

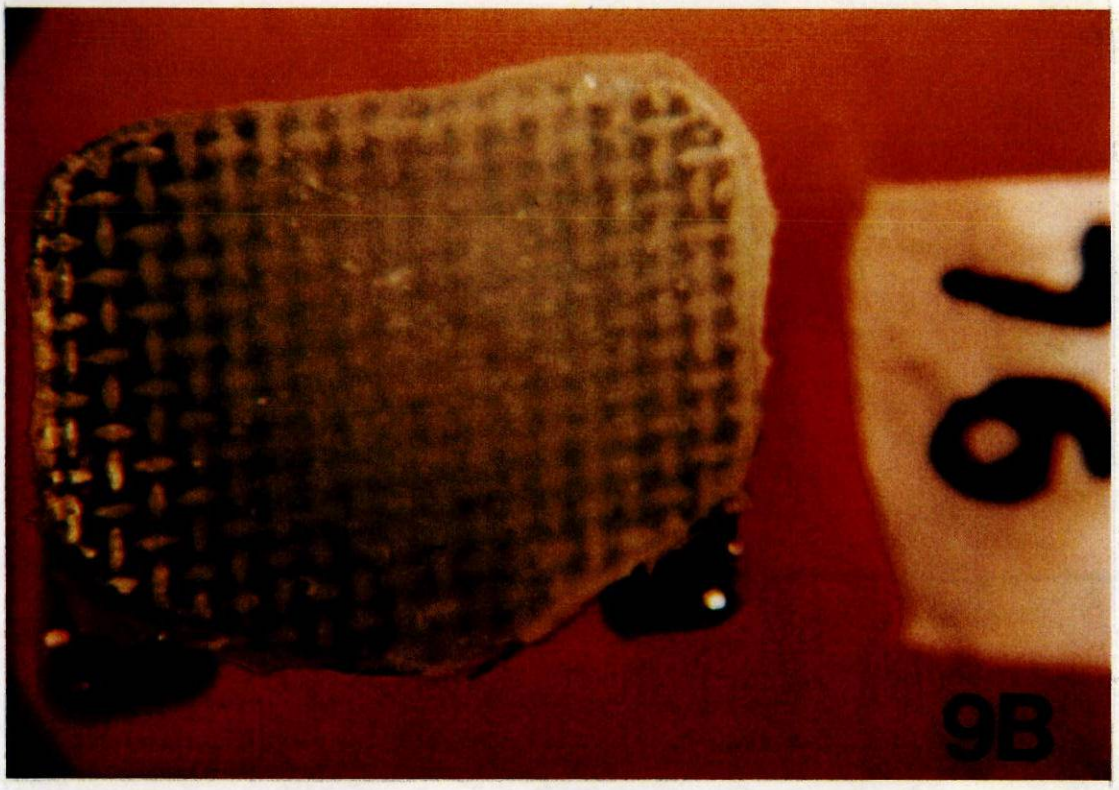

76
9B

Figure 9a. Photograph of debonded enamel surface of non etched sample at 12 X magnification

Figure 9b. Photograph of debonded bracket surface of non etched sample at 20 X magnification

DISCUSSION

Bond Strength

The acid etched mean bond strength found in the present study is 65.4 pounds (29.7 kilograms) with a standard deviation of 13.4 pounds. The area under the wide 100 mesh central incisor bonds was 20 square millimeters (4.0 mm x 5.0 mm). The mean bond strength 65.4 pounds can be converted to 1.5 kilogram per square milimeter, 14.71 MPa, or 291.3 Newtons. This compares favorably with the acid etched bond strengths of previous shear bond strength studies. Gwinnett[100] found a bond strength of 12.1 MPA using a mesh based bracket. Viazis et al.,[101] found a shear bond strength of 22.16 kilograms using metal meshed brackets. Other shear bond tests using mesh backed metal brackets have found mean bond strengths of 17.34 MPa,[102] 11.6 MPa,[103] 1.69 kilograms per square milimeter,[104] and 84 pounds.[105]

The results of the shear bond strength study shows a high standard deviation. Considerable variation in bond strengths in these and most bond strength studies suggests that bond strength Instron testing is a highly technique sensitive procedure. Variations in specimen preparation, film thickness of the adhesive, alignment of the testing apparatus and also in environmental conditions may all be factors when considering the large standard deviations often seen with these studies.[102,106]

As recommended by the subcommittee of standard test methods (May 6, 1967), the bovine enamel in the present study was ground flat which has

been found to produce a more uniform surface with a resulting smaller standard deviation when adhesive tests are performed.[107,108,109] Sanding the enamel surface flat produces a reproducible method of bond application, shear force measurement, and allows for a more even film thickness of the adhesive. There is also an improvement in the microscopic examination of the enamel surface of the samples.[110,111]

Bovine incisors were used in this study because they are a good substitute for human incisors. Bovine incisors have been used in shear bond strength testing by many researchers.[112,113,114] The Nakamichi et al.,[84] study was designed to evaluate the bovine incisor as a possible substitute in the adhesion test. This study showed no significant difference between human and bovine teeth, although in bovine teeth the mean bond strength values were always slightly lower than human teeth. This could be due to the slightly different etched prism configuration of bovine enamel which is smaller and more ovoid than the arcade shaped prisms of human tooth enamel. Bovine incisors provide a large flat consistent enamel surface that is amenable for bonding orthodontic attachments.

In theory when the head of the Instron device contacts the bracket in a parallel line of force to the adhesive bracket interface, only shear force occurs. However, there is most probably a simultaneous perpendicular tensile force produced as the bracket is being pulled away from the enamel surface. Small voids in the adhesive may be affected by this pulling force thus inserting some variability into the procedure.

The shear bond strength for the carbon dioxide laser etched surface in the present study was 11.8 pounds (5.4 kilograms) with a standard

deviation of 5.6 pounds. This value can be converted to 0.27 kilograms per square millimeter, 2.65 MPa, and 53 Newtons. The acid etch value is similar to that reported by Liberman[69] who reported values of 46 kilograms (SD=22.9) for his acid etched group which can be converted to 1.5 kilogram per square millimeter. Libermans value of 27.3 kilograms (SD=18.1) for his carbon dioxide group which can be converted to 0.9 kilograms per square millimeter is greater than that found in the present study. Liberman's study was conducted on human molars and premolars with a continous mode with resulting energy density of 35 Joules per square centimeter. This is a much greater amount of energy than that used in the present study. A continuous irradiation of the tooth surface may cause unacceptable pulp temperature increases.[62,65] Tessendorf[95] reported that with energy levels greater than 7 watts, a repetition rate over 10 pulses per second and an exposure time greater than 0.01 second you may get enamel charring. In the present study, when energy levels were raised above this threshold, charring of the enamel was noted. Liberman's study used a tensile test while the present study used a shear bond test. The two other single pulsed groups that Liberman evaluated did report similar bond strengths of 0.27 and 0.30 kilograms per square millimeter as those found in the present study. With the differences in the testing mode, teeth type and energy levels along with the variability often seen between different studies it is not possible to draw direct conclusions as to the reported higher bond strength of the continuous laser beam used by Liberman as compared to the present study.

A recent abtract published by MacDonald et al.,[115] reported on a comparative shear bond strength study of acid and carbon dioxide laser

etching. They reported mean acid etch shear values of 44.46 Newtons (10.0 pounds) and mean laser etched values of 35.06 Newtons (7.9 pounds). While the shear value of the carbon dioxide laser compared favorably with the present study, the acid etched shear value was much lower. Although they used a gel etching solution, it is debatable as to whether the low shear bond strength would be clinically acceptable. The laser energy settings of 8 watts and 0.015 second exposure are similar to that used in the present study, however human molar teeth were used. They concluded that at a p = 0.12 level that there was no significant difference between the two groups.

The mean shear bond value for the Nd:YAG laser used in the present study is 17.9 pounds (SD=5.4). This value can be converted to 8.1 kilograms, 0.41 kilograms per square millimeter, 4.02 MPa, and 79.4 Newtons. This compares favorably with the 4.6 MPa mean shear bond strength reported by White[76]. White's value was obtained using an energy level of 150 milijoules per pulse with a 20 hz repetition rate. This energy level is higher than that used in the present study (75 mJ/p, 15 Hz) and may account for the slightly higher mean bond strength. Although human molars were used the shear test parameters were similar. In another shear bond strength study, Hess[75] reported that the bond strength of liquid etched enamel was significantly greater than Nd:YAG laser etched enamel. Hess reported no significant difference between the Nd:YAG laser etched surface and that of the gel acid etched surface; however, no figures were given.

One possible explanation for the increased bond strength of the Nd:YAG laser treated teeth over the carbon dioxide laser treated teeth may be the surface application of the black ink initiator. This absorptive coating

on the Nd:YAG samples provided an area where concentration of the laser beam occurred exactly on the surface as the initiator absorbed the laser energy. The Nd:YAG lasers hand piece was moved back and forth as consistently as possible until all the initiator was removed. As the beam came in contact with the initiator a loud popping and cracking sound occurred and a bright point of reflected light was produced. Thus it was easy to focus the beam on the initiator using the popping, cracking and reflecting bursts of light as a guide. The carbon dioxide laser hand piece on the other hand was more difficult to monitor during laser beam application. Although the hand piece was moved over the enamel surface as consistently as possible there were probably more areas that did not receive direct laser pulses than with the Nd:YAG laser. Small red flashes were seen as the carbon dioxide laser passed over the enamel surface and a slightly frosty, uniform etched like appearance did result although the changes were subtle when compared with acid etching.

SEM Evaluation

The decreased bond strength of the laser etched samples is consistent with the SEM appearance and with the light microscope evaluation of bond fracture location. The SEM studies show a uniform consistent enamel change in the acid etched area which would provide for a maximum bonding surface area. The acid etched surface had a prism configuration that was smaller and more ovoid than human enamel which is consistent with other SEM studies. The Nd:YAG laser etched surface showed less uniformity that the acid etched surface but more than the carbon dioxide etched surface. This is consistent with the Instron shear test

results. Hess[74] and Myers[72] et al. reported similar morphologic changes after Nd:YAG laser etching under SEM examination. The carbon dioxide laser etched surfaces appeared much more like the non etched control group with some areas of crater formation which is also consistent with the Instron test results. Thus the SEM appearance of the four experimental and control groups was consistent with the Instron shear strengths measured. The acid etched group revealed a uniform consistent surface under SEM examination which is consistent with its high shear strength values. The high strengths achieved can be attributed to the numerous undercuts and areas available for composite adhesion. The Nd:YAG laser revealed a fairly uniform and roughened surface but not to the degree of the acid etched surface. This correlates with the decreased bond strength as compared to the acid etched group. The carbon dioxide group revealed an even less uniform and effected enamel surface than the previous groups. It can be concluded that this decrease in surface roughness can explain the accompanying decrease in bond strength. The non-etched control group had the smoothest surface under SEM observation and the lowest bond strength. Thus surface roughness is probably a major factor in determining shear bond strength.

Light Microscope Evaluation

Evaluation of the samples under the light microscope revealed that the acid etched samples break almost routinely at the composite/bracket interface while both the carbon dioxide and Nd:YAG laser etched groups along with the non etched control group fractured at the tooth/composite interface. Most bond strength studies have shown that acid etched bonded

brackets fracture predominantly at the composite bracket interface.[116,117,118] This is also consistent with both the Instron shear test and the SEM appearance of the various surfaces. It was noted that in some of the Nd:YAG laser etched samples there were infrequent small areas of composite remaining on the tooth surface, however there were no Nd:YAG samples where a majority of the composite remained on the tooth.

As previously stated both the carbon dioxide and Nd:YAG treated samples showed that the composite remained on the bracket and under the light microscope had a dull grayish appearance. Some of the Nd:YAG samples showed slightly dark areas on the bracket/composite surface where what appeared to be residual black initiator remained.

Although a vast majority of the initiator was removed during laser etching what appeared to be a very light thin amount of residue remained which could not be removed even with further application of the laser. It was determined that further laser irradiation to try to remove all the remnants of the initiator would require extensive additional energy application which would not only increase the variability but also extend the amount of time needed to etch the enamel surface with the laser to an unacceptable clinical length. As it was, the amount of time needed to etch the enamel surface with the Nd:YAG and the carbon dioxide lasers was approximately forty seconds. The actual time was dependent on the amount of enamel exposed as all the exposed enamel was laser etched. With regards to time savings it has been reported that perhaps up to a forty percent time savings could be obtained with laser etching over acid etching. A subjective evaluation by the present study investigator reduces this times savings to perhaps twenty percent with

the carbon dioxide laser and to even less with the Nd:YAG laser as it requires additional time to place the initiator, get an even film thickness by blowing air over the initiator and then waiting for the initiator to dry.

Another consideration is the ability to have an auxiliary apply the acid etch and to rinse the surface after sixty seconds while laser application would most certainly be performed by the dentist. Recent studies have also suggested that shorter acid etching times may produce comparable bond strengths which further erodes the time advantage of using a laser in place of acid etching.[119,120]

One advantage of using a laser to prepare a tooth for bonding of an orthodontic attachment is that the laser energy may decrease the solubility of the surrounding enamel. A common problem that occurs in orthodontic patients who have consistant poor oral hygiene is that of decalcification on the area surrounding the orthodontic brackets. This may lead to permanent white marks often shaped in a square mimicking the shape of the removed bracket. It has been reported that laser treating of enamel may increase the resistance to demineralization.[41,42,44]

The various types of lasers and the different units of measurements that are used along with the high degree of variation in bond strength measurements makes it difficult to compare results reported by different investigators. The newer lasers now being marketed provide more instrumentation to more accurately measure the amount of energy being applied to the tissues investigated. In the future, standard measurements will need to be developed in order to accurately compare the effects of the various lasers and the various power settings being used.

Acid etching produces a uniform etched surface with reliable and clinically effective bond strength for a low cost in a short period of time. In some states, it is also a procedure that can be delegated to an auxiliary. The amount of tooth enamel damage produced with acid etching is minimal. In the clinical setting, even with the fairly high bond strengths that can now be obtained, bracket failure is still a problem. Most clinicians agree that it would be desirable to obtain even higher bond strength with metal brackets. This area is being heavily investigated and many researchers are studying methods to increase bond strength. Under higher power settings laser irradiation can damage the enamel surface and deep penetration with possible pulp damage can occur. Thus, with the clinically unacceptable decrease in bond strength, increased cost, inability to delegate, and most probably a very limited time savings, one can conclude that the efficacy of laser etching as compared with that of acid etching is, at this time, very low. The use of lasers for such procedures is not recommended as a substitute for acid etching in preparation for bonding of orthodontic attachments.

CONCLUSIONS

The objectives of this study were to (1) compare in vitro the bond strengths achieved by laser and acid etching and (2) evaluate the surface characteristics of laser etched and acid etched enamel under a SEM. The following represents the major findings of this study.

1. Acid etching produced the maximum bond strength.
2. Etching with the Nd:YAG laser as well as the carbon dioxide laser produced much lower bond strengths than acid etching.
3. The Nd:YAG laser produced higher bond strengths than the carbon dioxide laser
4. Bond strengths produced by the lasers were not clinically acceptable based on this study.
5. Based on this study the Nd:YAG laser and the carbon dioxide laser cannot be recommended for preparation of enamel prior to bonding of orthodontic attachments.

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