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# THE EFFECT OF ArF-EXCIMER LASER IRRADIATION OF THE HUMAN ENAMEL SURFACE ON THE BOND STRENGTH OF ORTHODONTIC APPLIANCES

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## Abstract

This study investigated enamel laser conditioning as an alternative to acid etching in bracket therapy. In preliminary experiments optimal laser parameters for achieving a bond strength of 6-10 N/mm$^2$ were defined. Enamel surface morphology was assessed and the ablation depth was measured on serial enamel sections. Thirty human molars were exposed to 193 nm ArF-excimer laser radiation (energy density: 260 mJ/cm$^2$) by single pulse application of 23 nanoseconds. Thirty molars were etched with phosphoric acid (37%) for 60 seconds. The brackets from the treated molars and 30 untreated molars were debonded vertically for tensile bond strength measurement. Roughened enamel surfaces were attained by 450 and 900 laser pulses with a mean ablation depth of 10.13 ± 4.84 μm. After 1-10 laser pulses, the enamel surface appeared intact. The tensile bond strength was 6.63 ± 2.18 N/mm$^2$ in the laser-treated group (1 pulse), 8.75 ± 3.61 N/mm$^2$ in the acid-etched group, and 4.61 ± 3.15 N/mm$^2$ in the untreated group. We conclude a laser-selective ablation of the membranous enamel pellicle. Since the irradiated area can be adapted to bracket base and the enamel surface remains morphologically intact, pulsed ArF-excimer laser treatment seems to be superior to the acid etching technique.

**Key words**: Ablation, ArF-laser, bond-strength, bracket, enamel-pellicle, etching, enamel, human, phosphoric acid, electron microscopy, morphology.

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## Introduction

The acid etching technique of dental enamel was introduced by Buonocore (1955) and the basic mechanisms of acid-enamel interaction have been further investigated by Newman (1964). Since then, several variations of the applied acid, its concentration, and its application time have been studied with the aim of increasing the surface area by roughening and thus, improving the bond strength between the enamel surface and an adhesive (Newman, 1973; Dennison and Craig, 1978; Nordenvall *et al.*, 1980). Although the acid etching of enamel has meanwhile been developed to a standard procedure in clinical applications, some major problems have not been solved completely but can indeed be controlled by careful clinical handling.

Acid etching does have some disadvantages. Among these is the uncontrollable depth of etching (Diedrich, 1983), which can extend up to 100 μm into the enamel substance as published by Reinhard and Vahl (1979). Secondly, the pattern of etching type is unpredictable (Abendroth and Bößmann, 1979). Thirdly, Smith *et al.* (1976) could prove acid residues in the enamel substance, even after thorough irrigation of the teeth by the use of $^{32}$P-isotope labelling of the acid. This amounted to approximately 40% of the original acid concentration up to a depth of 50 μm. According to Smith *et al.* (1976) this residual acid is very likely to engender a long-term effect on the enamel, the final result of which is difficult to assess. Finally, in our experience, the geometry and the extent of the etched enamel area is hardly reproducible in a clinical setting.

As a consequence of these disadvantages of chemical etching, recent studies have been directed towards evaluate the feasibility of enamel surface modification by laser treatment. The initial studies concentrated on the laser-tissue interactions and afforded mainly morphological and physical data on enamel surface condition. With the aim of enamel roughening, laser-specific enamel surface alterations have been studied for different laser wavelengths and various sets of parameters, whereby the application of excimer lasers have recently gained

**Table 1.** Grouping of the study and size of samples.

| Tensile bond strength measurements; n = 145 (preliminary experiments: 11 groups) | |
|---|---|
| Preliminary laser-experiments | n = 55 (11 x 5) |
| Main laser-experiment | n = 30 |
| Acid-etched control group | n = 30 |
| Untreated control group | n = 30 |
| **Morphological analyses; n = 66** | |
| Measurement of ablation depth | n = 22 (11 x 2) |
| Qualitative surface morphology | n = 44 (11 x 4) |

**Table 2.** Parameters of ArF-excimer laser irradiation (193 nm).

| | |
|---|---|
| Power / pulse | $9.2 \times 10^6$ W |
| Energy / pulse | 41.3 mJ |
| Pulse duration | 23 ns |
| Pulse frequency | 5 Hz |
| Energy density | 260 mJ/cm$^2$ |
| Spot size (diameter) | 4.5 mm |
| Number of pulses | 900, 450, 100, 80, 60, 40, 20, 10, 5, 2, 1 |

increasing interest. Neev *et al.* (1991) and Feuerstein *et al.* (1992) investigated the ArF-excimer laser (193 nm), Liesenhoff *et al.* (1990) evaluated the XeCl-excimer laser (308 nm), and Ruppenthal *et al.* (1991) examined the KrF-excimer laser (248 nm) and compared it to the ArF-excimer laser (193 nm) in a later study (Ruppenthal *et al.*, 1992).

Other groups have primarily evaluated the bond strengths between the laser-treated enamel surface and different resins for application in orthodontic and restorative dentistry. Liebermann *et al.* (1984) and Altshuler *et al.* (1989) treated enamel surfaces with the $CO_2$ laser and conducted shear bond strength tests. Frentzen *et al.* (1989) evaluated the effect of pulsed ArF-excimer laser enamel treatment on the tensile bond strength. Recently, Roberts-Harry (1992) as well as von Fraunhofer and Orbel (1993) analyzed the shear bond strength after pulsed Nd:YAG laser treatment of human enamel, while Keller and Hibst (1993) evaluated the efficacy of the pulsed Er:YAG laser in a tensile bond strength experiment. However, not a single study could prove a convincing superiority of laser treatment as compared to conventional acid etching. This is surprising because, at least for the ArF-excimer laser (193 nm) and KrF-excimer laser (248 nm), the morphological results are very encouraging.

Therefore, it was the aim of this study to develop a laser-mediated modification of the enamel surface to such a degree that it could afford a clinically useful alternative which could replace acid-etching for orthodontic bracket bonding.

## Materials and Methods

The studies mentioned above have confirmed the photoablative properties of the ArF-excimer laser (193 nm) and KrF-excimer laser (248 nm) resulting in a satisfactory roughening of the enamel surface accompanied by negligible thermal side effects as mentioned by Neev *et al.* (1991), Feuerstein *et al.* (1992), and Ruppenthal *et al.* (1992). However, a determination of average thermal response of ablated enamel surfaces was reported only by Neev *et al.* (1991). Moreover, none of these authors described any negative side effects of the laser irradiation on oral soft tissues.

In prior experiments, we investigated the features of enamel surface roughening with three different excimer lasers (ArF-, KrF- and XeCl-excimer laser; unpublished data) in order to select the best of the currently available excimer lasers for this purpose. Morphologically, the most substantial increase of the enamel surface area was achieved by the ArF-excimer laser (193 nm).

Caries-free, first, second and third permanent mandibular and maxillary molars freshly extracted for orthodontic, parodontal or surgical reasons were used. After mechanical cleaning of the buccal enamel faces by polishing with pumice, the teeth were selected according to the following criteria: (1) no previous restorations; (2) no dental calculus; (3) no discolorations or hypoplasia; and (4) no macroscopically perceivable enamel cracks. By these strict preconditions, a total of 211 molars could be selected from 537 extracted teeth; these molars were subdivided in different experimental groups (Table 1).

For bond strength measurements, a total of 145 molars were embedded in cube-shaped plastic blocks with their buccal faces upwards. The teeth were stored in Ringer solution at room temperature under sterile conditions. The medium was changed daily in order to avoid any bacterial overgrowth. A total of 11 preliminary experiments served for definition of the laser parameters with the aim of achieving a bracket bond strength in the clinically relevant range of 6-10 N/mm$^2$ for orthodontic appliances (Reynolds, 1975). In these 11 groups of 5 molars each, we irradiated the enamel surface by an 193 nm ArF-excimer laser (Lextra, Lambda Physics, Göttingen, Germany) using 11 variations of the pulse number without changing other parameters (Table 2).

In order to guarantee a reproducible position of the laser beam on the tooth surface, we used a visible, coaxial HeNe-pilot-laser which was centered on the buccal face of the teeth. After evaluation of the preliminary bond strength experiments, we decided that a single pulse was sufficient to produce the desired clinically relevant bond strength; therefore, this parameter was selected for the main experiment.

For the morphological analyses, a total of 66 molars were irradiated with parameters according to the preliminary experiments and also subdivided into 11 groups (Table 1). For qualitative morphological evaluation of the laser-treated enamel surfaces, a total of 44 molars were prepared for conventional scanning electron microscopy (SEM) by sputtering a 30 nm thick gold layer. For measurement of the ablation depth, parallel serial slices were cut from the remaining 22 molars perpendicular to the irradiated surface using a diamond-coated precision saw (thickness of slices = 0.5 mm; loss of substance due to band thickness = 0.2 mm). After sawing, the slices were polished gently to remove only the smear layer and prepared for SEM. Microphotographs were taken of all slices and the depth of the microlesions was measured for each slice for approximation of the mean ablation depth.

In the main experiment, we bonded Ormesh stainless steel brackets (Ormco Company, Glendora, California) to the centre of the irradiated area of 30 embedded molars immediately after laser pulse application and subsequent drying by using Concise-orthodontic-bonding-system (Nr. 1960, 3M Ltd., St. Paul, MN, USA). Excessive adhesive was removed mechanically shortly before termination of the polymerization process (at room temperature) by cutting with sapphire microscalpels in order to guarantee that the extension of the adhesive corresponded to the bracket base (4 x 2 $mm^2$).

As a first control group, we used 30 embedded molars for acid etching. Thirty-seven percent $H_3PO_4$-etching gel (Scotchbond, 3M) was applied to the buccal enamel surface for 60 seconds, and after subsequent irrigation, the molars were dried prior to bonding of the brackets. An etching area larger than the bracket base area ($> 4 \times 2$ $mm^2$) was chosen. As a second control group, we used 30 embedded molars which were bonded without previous treatment in order to estimate interindividual variability of the sound enamel surface morphology and its possible influence on the bond strength of untreated teeth.

In order to simulate *in vivo* conditions of the oral cavity all molars were stored in Ringer solution for a mean period of 48 hours prior to debonding of the brackets.

For bond strength measurements, we used a microprocessor-controlled universal testing machine (Otto Wolpert Ltd., Ludwigshafen, FRG). The plastic blocks, with the embedded molars, were fixed in the sample holder of the universal testing machine, and a vertical traction with a speed of 1 mm/min was applied to the bracket. The tensile bond strength was defined as the ratio of the measured maximal tensile-force and the fracture face area of the adhesive, which was measured by stereomicroscopy for every bracket after debonding. In the main laser experiment, as well as in both control groups, we only estimated bond strength values for brackets whose fracture face lay at the interface between adhesive and enamel surface. For statistical evaluation of our data, we used a one-way variance analysis (Scheffe test; level of significance, $p \leq 0.05$).

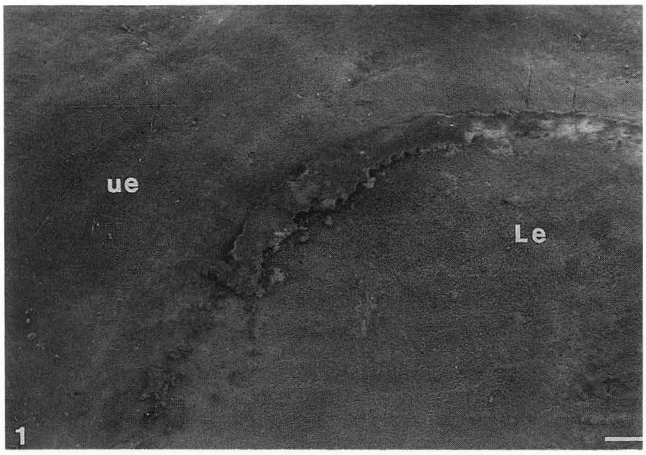
## Results

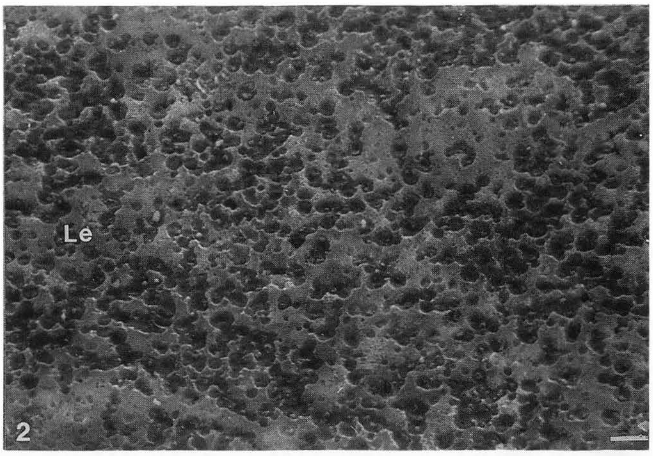
### Morphological findings

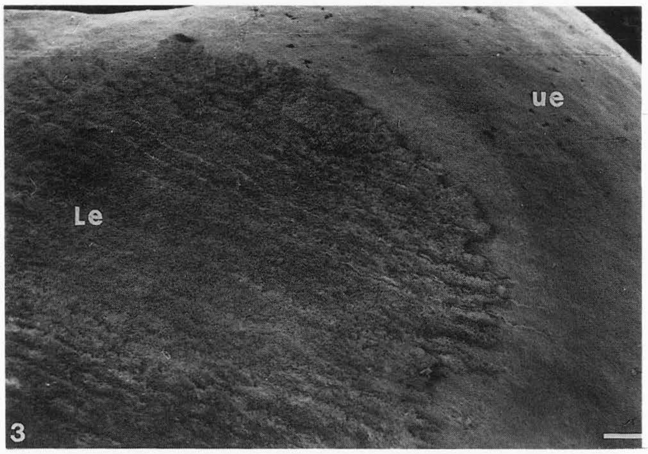
The morphological feature of enamel surfaces after irradiation with a varying number of pulses in the preliminary experiments was very similar in the group of 20-100 laser pulses. In Figure 1, a sector of the irradiated circular area is visible at a low magnification. A clear margin of the irradiated area allowed one to distinguish a laser-treated enamel surface with a rough appearance from a smooth, untreated enamel surface. At higher magnification (Fig. 2), a pattern of shallow depressions with an average diameter of 5 $\mu m$ was observed occurring either as single formations or as confluent groupings.

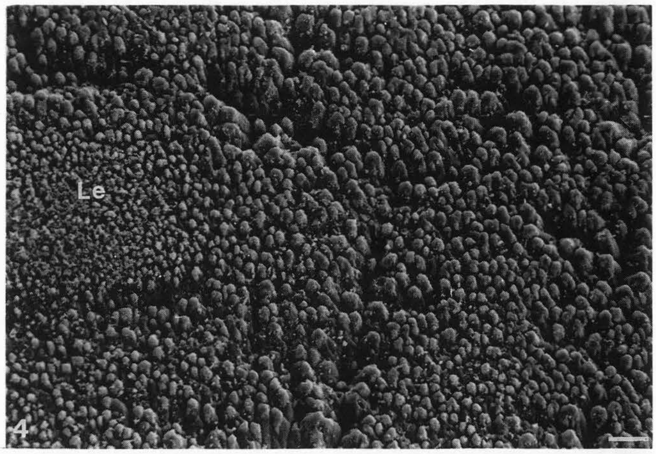
In the groups of 450 as well as 900 laser pulses, we found a slightly higher grade of surface roughening in the irradiated area which was also sharply demarcated from the surrounding untreated enamel surface (Fig. 3). Furthermore, Figure 3 shows that the regular pattern of imbrication lines and perikymata was just visible and had therefore been preserved even after application of 900 laser pulses. At higher magnification (Fig. 4), the alteration of the irradiated enamel surface was more prominent compared to the group described above. The morphological feature was characterized by cleft-like microlesions between cone-shaped protrusions resembling the type II acid etching pattern (peripheral etching type) according to the classification of Silverstone (1982).

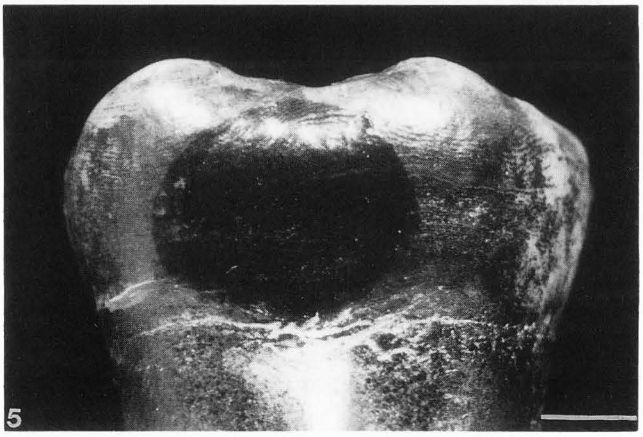
In the group of 1-10 laser pulses, we observed no signs of surface alterations in survey micrographs although the margin of the irradiated area was detectable as a faint line with a slightly brighter appearance compared to the surrounding enamel. However, this change in the optical property of the irradiated area was more clearly visible immediately after gold sputtering of the molars (Fig. 5). Since this discoloration was certainly due to a laser-induced change of light reflection in the irradiated area as a consequence of some surface modification, we carried out a detailed investigation of the

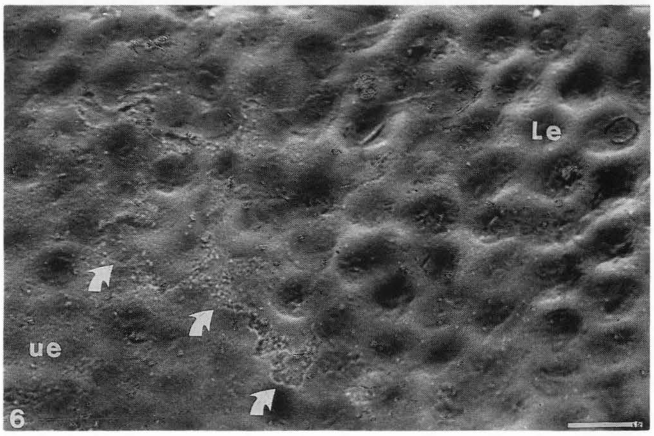












**Figures 1 and 2**. Survey (**Fig.** 1) and detail (**Fig.** 2) scanning electron micrographs of ArF-excimer laser-irradiated human enamel (100 pulses). le = laser-treated enamel surface, ue = untreated enamel surface. Bars = 100 μm (Fig. 1) and 10 μm (Fig. 2).

**Figures 3 and 4**. Survey (**Fig.** 3) and detail (**Fig.** 4) scanning electron micrographs of ArF-excimer laser-irradiated human enamel (900 pulses). le = laser treated enamel surface, ue = untreated enamel surface. Bar = 100 μm (Fig. 3) and 10 μm (Fig. 4).

**Figure 5**. Photograph of ArF-excimer laser irradiated human molar after gold sputtering (1 pulse). Bar = 10 μm.

**Figure 6** Detail scanning electron micrograph of ArF-excimer laser-irradiated human enamel (1 pulse). le = laser-treated enamel surface (Note clearly visible shallow enamel pits), ue = untreated enamel surface, arrows = margin of irradiated area. Bar = 10 μm.

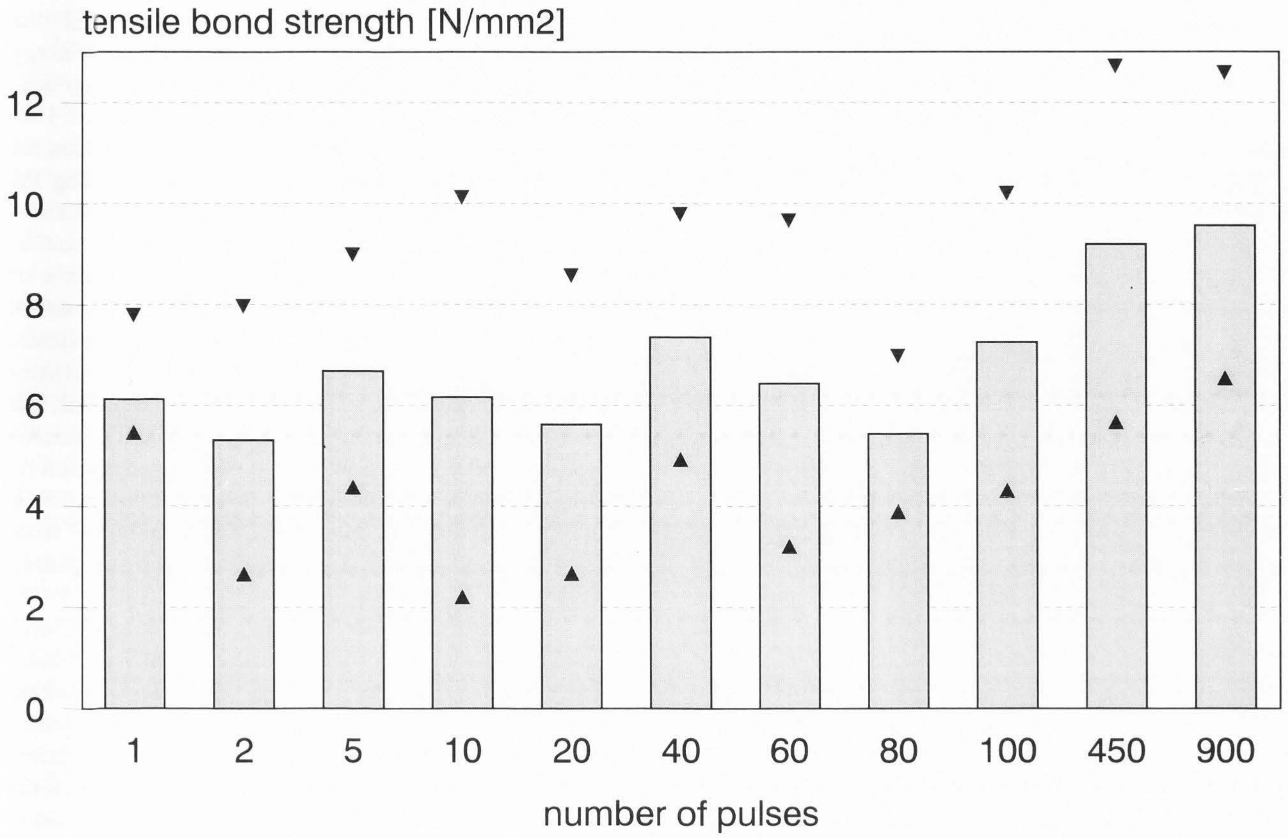


**Figure 7.** Measurement of tensile bond strengths in the preliminary experiments. The triangles mark the range of standard deviations.

**Table 3.** Measurement of tensile bond strength.

| grouping | enamel treatment | mean [N/mm$^2$] | standard deviation |
|---|---|---|---|
| main experiment | 1 laser pulse | 6.63 | 2.18 |
| control (etching) | 37% $H_3PO_4$ | 8.75 | 3.61 |
| control (untreated) | ----- | 4.61 | 3.15 |

peripheral laser area in order to detect a morphological correlate in the scanning electron micrographs. At high magnifications, we indeed succeeded in detecting certain locations along the marginal laser area which showed a difference in enamel surface relief. Here, the regular surface feature of shallow enamel pits (Boyde, 1989) was covered and partially masked by a thin membranous layer in the non-irradiated area, whereas these pits were clearly visible and more prominent in the irradiated area (Fig. 6).

## Measurements of ablation depth

The evaluation of the slices cut perpendicular to the irradiated surface was conducted in order to assess the ablation depth of enamel substance by laser irradiation. In the groups of 1-10 as well as 20-100 laser pulses, we could not measure any depths of microlesions since the contour of the irradiated area showed such small variations that distinct differences compared to the untreated surface level could not be discerned.

Conversely, in the groups of 450 and 900 laser pulses, we found the microlesions to be wedge-shaped with a very even appearance and only minor deviations of width. The enamel ablation depth, after ArF-excimer laser irradiation, measured on $n = 720$ microlesions (30 deepest lesions/slice, 6 slices/molar, 4 molars) was $10.13 \pm 4.84$ $\mu$m.

## Measurements of tensile bond strength

As shown in Figure 7 for the preliminary experiments, the mean tensile bond strength did not increase as a function of the pulse number, but showed higher values only in the groups of 450 and 900 laser pulses.

By statistical evaluation (Scheffe test, level of significance $p \leq 0.05$), the mean tensile bond strength of the main experiment did not differ significantly from that of the acid-etched group but was significantly higher than the mean value of the untreated control group (Table 3).

## Discussion

This study was conducted in order to develop an alternative to acid etching of the enamel surface for orthodontic appliances. The clinically relevant range of bond strengths of the bracket-adhesive-enamel complex was supposed to lie between a minimum of 6 N/mm$^2$ (Reynolds, 1975) and a maximum of 10 N/mm$^2$ in order to avoid enamel fracturing if the debonding forces exceed the enamel breaking strength, for which Bowen and Rodriquez (1962) have determined a value of 10.34 ± 1.47 N/mm$^2$. Apart from the untreated control group, almost all laser treatments, as well as the acid treatment, resulted in the desired range of bond strength. Surprisingly, after application of 1-10 pulses, the laser-irradiated enamel did not display a roughened surface similar to that displayed after acid etching; instead, its surface resembled the untreated control enamel at first sight, but, in detailed investigation, turned out to be devoid of a superficial membranous layer detectable in neighbouring untreated areas. Presumably this membrane corresponds to the acquired enamel pellicle which has been the object of extensive investigations by Jenkins (1978). This pellicle has a mean thickness of 1 $\mu$m and protrudes into the enamel by a network of dendritic processes termed "subsurface cuticle" by Meckel (1965). Moreover, Silverstone (1982) has reported the penetration of exogenous organic material into the so-called "focal holes" (i.e., physiological, isolated deep pits in the enamel surface), which are commonly found along the surface layer of sound enamel and are usually 4-5 $\mu$m wide and 5-10 $\mu$m deep (Boyde, 1989). Due to its high adhesive property to the enamel surface and because of the surface irregularities, this pellicle is hardly removable by mechanical cleaning; therefore, residues of the pellicle are supposed to persist even after polishing the tooth with pumice (Jenkins, 1978).

Our scanning electron microscopy observations support the hypothesis that this pellicle can be removed by just a single ArF-excimer laser pulse with an energy density of 260 mJ/cm$^2$. This energy density is sufficient for an effective ablation of soft tissue according to Kraus *et al.* (1986), who were able to calculate the threshold of ablation (i.e., minimal pulse energy density producing a detectable ablation) after pulsed ArF-excimer laser irradiation of human cornea, already at an energy density of 46 mJ/cm$^2$. Likewise, Neev *et al.* (1991) reported plumes of smoke at the first 3-4 pulses during ArF-excimer laser irradiation of the enamel surface and concluded that this was due to the laser's ability to selectively remove residual organic material from the more laser-resistant mineral substance. Contrary to the soft tissues, the ablation of mineral substance requires a much higher energy density. For the pulsed ArF-excimer laser, Frentzen *et al.* (1989) calculated an ablation depth of 0.15 $\mu$m/pulse for human enamel at an energy density of 6000 mJ/cm$^2$, which exceeds the energy density required for soft tissue ablation by a factor of 130.

In conclusion, we assume a selective mechanism for laser ablation which has the property of removing the organic pellicle, including its subsurface protrusions, without producing microscopical lesions of the underlying enamel mineral. Thus, an enamel surface free of pellicle residues offers an ideal precondition for entire wetting by an adhesive, which guarantees the intimate contact essential for maximal adhesion forces between apatite crystals and the resin molecules. Moreover, the bond strength may be increased by mechanical microretention which is predominantly due to penetration of adhesive into a communicating system of subsurface micropores and microclefts as well as "focal holes" from which the organic filling has been removed by the pulsed ArF-excimer laser.

Other authors failed to attain a bond strength comparable to our results by application of different laser wavelengths to the enamel surface. Since those workers have applied a continuous wave mode, or long-pulsed mode, they may have induced a predominantly photothermic effect which obviously results in a smooth, glass-like ("vitrified") enamel surface with the consequence of low bond strength values as reported by Liebermann *et al.* (1984) for the $CO_2$-laser with a mean bond strength of 2.65 N/mm$^2$ or by White *et al.* (1991) for the Nd:YAG-laser with a mean bond strength of 4.52 N/mm$^2$.

Surprisingly, Frentzen *et al.* (1989) published a mean bond strength of only 3 N/mm$^2$ for the pulsed ArF-excimer laser using parameters comparable to our study (pulse number = 1000, energy density/pulse = 318 mJ/cm$^2$). Since they also reported a mean bond strength of 4 N/mm$^2$ after acid etching (37% $H_3PO_4$, 60 seconds), this discrepancy seems to be due to different experimental conditions or a systematic error of measurement.

On the other hand, Altshuler *et al.* (1989) reported a bond strength range of 6.9-8.7 N/mm$^2$ after pulsed $CO_2$-laser treatment. Likewise, von Fraunhofer and Orbel (1993) calculated a maximal bond strength of 12.8 ± 0.24 N/mm$^2$ after pulsed Nd:YAG-laser treatment, while Keller and Hibst (1993) published a maximal bond strength of 9.25 N/mm$^2$ after pulsed Er:YAG-laser irradiation. However, these authors did not completely recommend the "laser-etching technique," and Roberts-Harry (1992) claimed, in a clinical laser experiment, that using the pulsed Nd:YAG-laser for "etching" teeth prior to bonding of orthodontic brackets took considerably longer, was less reliable in terms of bond strength and produced more discomfort than conventional acid-etching.

However, according to our results, the pulsed ArF-excimer laser produced bond strengths in the clinically relevant range and is superior to the acid-etching technique since the enamel exhibits a micromorphologically intact surface after laser irradiation. Secondly, the geometry of the irradiated area can be accurately adapted to the base area of the bracket. Finally, conventional acid etching produces a small but detectable pulpal reaction in comparison to untreated controls 1-6 weeks after etching (Arcoria *et al.*, 1992). Indeed, after pulsed ArF-excimer laser treatment, these authors found a similar histological pulp response but had applied 600 pulses with a pulse energy density of 45000 $mJ/cm^2$, which exceeds our parameter (energy density = 260 $mJ/cm^2$) by a factor of 173.

We conclude that these favorable results should encourage further *in vitro* studies and successive animal studies to optimize standardization of parameters and reproducibility of results as well as to exclude biological side effects in the oral cavity. Presently, a prospective study with the aim of determining the significance of thermocycling on the bond strength and the effect of laser-irradiation on a prepared tooth surface (mechanical or chemical removal of the enamel pellicle) is in progress.

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## Discussion with reviewers

**T.F. Watson**: What other techniques could have been used to evaluate the adhesive interfaces?

**Authors**: Cross-sections through the bracket-adhesive-enamel complex can be evaluated for shape and extent of adhesive tags by polarized light, confocal laser microscopy, cathodoluminescence or by recently developed Fourier transform infrared photoacoustic spectroscopy for determination of mineral/resin ratio.

**T.F. Watson**: How can the authors be sure that the removed membranous surface is attributable to the organic pellicle and not to the aprismatic surface enamel zone?

**Authors**: In our opinion, there is no evidence from which to postulate an ablation of the aprismatic enamel by laser energy. First, the enamel surface was exposed to the laser energy of only one pulse, which is far too low for ablation of mineral substance as already mentioned in **Discussion**. Secondly, the surface morphology of the irradiated area (see, Fig. 6) is very smooth and exhibits the typical honeycomb-shaped pattern of shallow enamel pits which represent the impressions of former apical portions of ameloblasts' cell bodies after retraction of their Tomes' processes. In case of an ablation of the aprismatic enamel, both these surface features would not have been visible.

**U. Keller**: In the recent literature, the mean value of tensile strength of composites after acid etching of the tooth surface is 10 N/mm$^2$. Is there another experimental method used in this study because only a mean value of 8.75 N/mm$^2$ is reached?

**Authors**: In this study, the tensile bond strength was measured with the aid of a testing machine, which is widely accepted for conducting of bond strength tests in material sciences. Regarding the mean value of tensile bond strength, a comparison to literature data should be limited to identical conditions of enamel etching (i.e., the type and concentration of acid, the duration of etching process) and bracket bonding (i.e., the type of adhesive, the degree of pressure and temperature during polymerization, the period and the chemical milieu of storage prior to debonding for *in vitro* studies). Indeed, some variations in technical processing or in material result in a wide range of mean bond strength values (e.g., 4.6-16.9 N/mm$^2$) as reported by Bishara *et al.* (1989) and Jassem *et al.* (1981).

**U. Keller**: For the study, an irradiation spot size of 4.5 mm in diameter has been chosen. Since the tooth surfaces are not planed, the experimental results should include both the tensile and the shear bond strength.

**Authors**: In order to simulate the clinical situation, we performed this investigation on natural, sound enamel surfaces and not on planed sections or slices of teeth. Due to the slightly convex surface of the chosen buccal molar faces, the results of the bond strength values will contain a minor contribution of the shear bond strength.

**U. Keller**: From a theoretical point of view the optimal energy density should be just below the ablation threshold of the inorganic enamel compound. In this case, the maximum etching depth/pulse could be achieved, probably leading to a higher tensile strength (as observed for 450 pulses with lower energy). What was the reason for choosing this energy density used with respect to the ablation threshold of organic and inorganic compounds?

**Authors**: It was the aim to modify the enamel surface with an energy density causing minimal lesions of the mineral compound but simultaneously yielding the desired bond strength. Therefore, we applied an energy density which was distinctly lower than the ablation threshold of the enamel substance, which has been approximated by Frentzen *et al.* (1989) to be 6 J/cm$^2$. On the other hand, the energy density should surpass the ablation threshold of organic material or soft tissue respectively, which has been approximated by Kraus *et* *al.* (1986) to have a value of 46 mJ/cm$^2$.

**T.D. Myers**: Considering that the authors' aim was to develop a clinically useful alternative to acid etching, how feasible it would be for a dentist to use the present ArF laser technology in the office setting?
**Authors**: The present investigation was designed as a pilot study for the project of laser conditioning of tooth enamel. Therefore, it has an experimental character and general clinical application cannot yet be recommended since the problem of suitable mechanical handling by a dentist by means of a flexible laser fibre has not been definitely solved. However, transmission via articulated mirror arms has been used for more than 10 years in routine intratracheal $CO_2$-laser surgery. The same delivery system has been developed for the ArF-excimer laser (e.g., for cornea surgery) and permits good handling. Moreover, new materials for flexible fibres are being developed (e.g., flexible circonfluorid-fibres for Er:YAG-lasers) so that appropriate fibres suitable for the ArF-excimer laser can be expected in the near future.

**T.D. Myers**: Acid etch techniques produce adequate bond strengths and are very cost-effective. Is there a cost justification for using the ArF excimer laser for this procedure?.
**Authors**: Under an economic-financial aspect, the utilization of conventional acid-etch technique seems at present to be more rational than the laser technique in a normal dental practice.

**T.D. Myers**: What laser delivery system was used?
**Authors**: The delivery system of the applied type of excimer laser was composed of a fixed transmission system with bending mirrors and an applicator equipped with a homogenizer and a circle-aperture as well as a zoom objective for projection onto the tooth surface.

**T.D. Myers**: Of what direct relevance to oral soft tissue is the ablation threshold of the human cornea?
**Authors**: Since the histological structure of the human cornea bears resemblance to that of oral soft tissues, it seems likely to assume also similar optical properties. Consequently, the application of laser light with an energy density above the ablation threshold of human cornea (46 mJ/cm$^2$) is supposed to damage oral soft tissues if directly exposed to the radiation.

**T.D. Myers**: Differences in recorded results between Frentzen *et al.* (1989) and the authors are acknowledged as possibly due to a systematic error of measurement. What assurance can the authors present that their results do not also suffer from a systematic error of measurement in the other direction?
**Authors**: Reviewing the relevant literature, we found the values reported by Frentzen *et al.* (1989) for the bond strength after laser treatment and after acid etching to lie distinctly lower than those obtained by other groups with comparable experimental conditions. At least, the value after acid etching is improbable since the use of $H_3PO_4$ (60 seconds) is generally accepted in orthodontic practice and results in a bond strength between 8 and 10 N/mm$^2$.

**T.D. Myers**: It is well documented that acid-etched enamel will remineralize after a short period of time. What happens to laser-modified enamel surface over time? Does it also remineralize? Is the lased enamel more susceptible to caries?
**Authors**: According to our literature overview, we cannot cite any published data on time-dependent alterations of laser-irradiated enamel surfaces exposed to the environment of the oral cavity. However, we assume a similar chemical process of remineralization where the morphology of laser-treated enamel surfaces resembles the acid-etched relief. Regarding the caries-susceptibility of lased enamel, an increased resistance to artificially produced caries-like lesions is well documented for treatment by the $CO_2$-laser, Nd:YAG-laser, Krypton-laser and Argon-laser but has not been investigated for excimer lasers hitherto.

**T.D. Myers**: The authors state: "The geometry of the irradiated area can be accurately adapted to the base area of the bracket." Can this statement be extrapolated to an *in vivo* clinical setting?
**Authors**: By equipping the laser transmission system with an aperture of suitable shape and size, any desired geometry of the irradiated area can be accurately projected onto the tooth surface. This method can also be extrapolated to an *in vivo* clinical setting by using different apertures for the bracket bases of the standard bracket-types used in dental practice.

**J.M. White**: Why was the range of 6-10 N/mm$^2$ chosen? Are there references to support this range? What is the significance of weaker or stronger bond strength measurements?
**Authors**: The desired range of bond strength between 6 and 10 N/mm$^2$ has been defined for orthodontic appliances to prevent failure during periods of orthodontic treatment. A minimal bond strength of 6 N/mm$^2$ is necessary to avoid bracket-adhesive fractures due to masticatory forces, which do not exceed 45 N under physiological conditions according to Newman (1965). As already mentioned in **Discussion**, a maximum bond strength of 10 N/mm$^2$ should not be exceeded in order to avoid enamel fractures during bracket debonding.

**J.M. White:** Was the bonding adhesive the first, second or third generation of this product? Why was this product chosen over others?
**Authors:** The present bonding adhesive belongs to the first generation of the applied product and was composed of pure Bis-GMA monomer and a high proportion of inorganic filler (70% $SiO_2$). It was chosen for this study since products with a high inorganic filling show a significantly higher bond strength between adhesive and acid-etched enamel than products with a low filling component according to Diedrich (1983).

**J.M. White:** Why were multiple laser pulses studied? Did a plasma form? What were the temperatures at the surface or in the pulp from these exposures? Are these temperatures detrimental?
**Authors:** In order to reduce any enamel mineral lesions to a minimum, we chose a constant energy density below the threshold of ablation for 193 nm irradiation. Therefore, we decided to vary the pulse number and to test whether the desired range of bond strength could be achieved at certain pulse rates. We renounced the measurement of a plasma formation since it was not of direct interest to the aim of the present study. From a theoretical-physical point of view, the formation of a plasma is indeed possible since the preconditions for its formation are fulfilled by the setting of this study (power density $\geq 10^7$ W/cm$^2$). It is almost impossible to measure the temperature at the enamel surface precisely, and a mathematical calculation can give only a rough idea of the temperature values reached since the deposition of energy in a small volume of the surface will increase the temperature extremely rapidly (pulse duration: 23 ns) but will immediately be transformed into mechanical energy by sudden expansion resulting in a microexplosion or a pressure wave without any thermal exchange. Moreover, the photon-energy of 193 nm has a value of 6.4 eV and is high enough to break ionic bonds in hydroxyapatite. Therefore the deposited energy could theoretically be completely transformed into mechanical energy without any thermal side effects.

An increase in pulp temperature can only be due to the relatively slow process of thermal conduction from the enamel via the dentin. By means of a thermal probe inserted into the pulp, Frentzen *et al.* (1990) recorded pulpal temperature rises by only 5°C *in vitro* after ArF-excimer laser irradiation of the enamel surface. They applied an energy density of 10 J/cm$^2$, which exceeds the energy density of our study by a factor of 38.5, whereas their pulse rates lay in the same range. However, even a pulpal temperature rise of 5°C has been proven to be innocuous for pulp viability according to Zach and Cohen (1965). We would expect no adverse pulpal tissue response after ArF-laser treatment with only 1 pulse because a direct photochemical damage can be excluded due to the high absorption coefficient of enamel and resulting low penetration depth of the ArF-laser radiation. Any photothermal effects are negligible as discussed in the previous answer to your question.

**J.M. White:** Below plasma formation, was there physical modification of the surface? How do the authors account for the linear effects below the plasma and for non-linear effects at and above plasma formation?
**Authors:** We could observe neither features of photoacoustic effects (i.e., cracks or chipped-off enamel particles) nor photothermal effects (i.e., glaze-like vitrifications or charred areas) in the vicinity of the irradiated area. Linear effects are based on absorption and are well predictable because energy density and laser effects follow a defined mathematical correlation. Conversely, non-linear effects are multi-photon effects with hardly predictable biological results due to photodisruption after plasma formation (optical breakdown).

**J.M. White:** How did the laser modification compare to acid modification? Did the laser treatment overcome the stated limitations of acid, or was it equivalent? The authors state that the ArF-laser produced acceptable bond strength and is superior to the acid-etching method. The data presented does not support this last conclusion. How was the laser approach superior?
**Authors:** Only after application of 450 and 900 laser pulses, did we observe surface modifications comparable to those after acid etching. In our opinion, the ArF-laser treatment (1 pulse) overcomes all limitations of acid etching and, moreover, has the substantial advantage of avoiding any injuries to the enamel surface. Indeed, the achieved bond strength of lased enamel (1 pulse) is not superior to the acid-etched control group but lies well in the desired range of clinically required bond strength.

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