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Abstract: **OBJECTIVE:** The aim of this study was to screen CO(2) laser (10.6 m) parameters to increase enamel resistance to a continuous-flow erosive challenge. **BACKGROUND DATA:** A new clinical CO(2) laser providing pulses of hundreds of microseconds, a range known to increase tooth acid-resistance, has been introduced in the market. **Methods:** Different laser parameters were tested in 12 groups (n=20) with varying fluences from 0.1 to 0.9 J/cm(2), pulse durations from 80 to 400 s and repetition rates from 180 to 700 Hz. Non-lased samples (n=30) served as controls. All samples were eroded by exposure to hydrochloric acid (pH 2.6) under continuous acid flow (60 L/min). Calcium and phosphate release into acid was monitored colorimetrically at 30 sec intervals up to 5 min and at 1 min intervals up to a total erosion time of 15 min. Scanning electron microscopic (SEM) analysis was performed in lased samples (n=3). Data were statistically analysed by one-way ANOVA (p<0.05) and Dunnett's post-hoc tests. **RESULTS:** Calcium and phosphate release were significantly reduced by a maximum of 20% over time in samples irradiated with 0.4 J/cm(2) (200 s) at 450 Hz. Short-time reduction of calcium loss (1.5 min) could be also achieved by irradiation with 0.7 J/cm(2) (300 s) at 200 and 300 Hz. Both parameters revealed surface modification. **CONCLUSIONS:** A set of CO(2) laser parameters was found that could significantly reduce enamel mineral loss (20%) under in vitro erosive conditions. However, as all parameters also caused surface cracking, they are not recommended for clinical use.

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Screening of CO₂ laser (10.6 µm) parameters for prevention of enamel erosion

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Abstract

Objective: The aim of this study was to screen CO₂ laser (10.6 μm) parameters to increase enamel resistance to a continuous-flow erosive challenge. **Background data:** A new clinical CO₂ laser has been introduced in the market providing pulses of hundreds of microseconds, range known to increase tooth acid-resistance. **Methods:** Different laser parameters were tested in 12 groups (n=20) with fluences varying from 0.1 to 0.9 J/cm², pulse durations from 80 to 400 μs and repetition rates from 180 to 700 Hz. Non-lased samples (n=30) served as control. All samples were eroded by exposure to hydrochloric acid (pH 2.6) under continuous acid flow (60 μl/min). Calcium and phosphate release into acid was monitored colorimetrically at 30 s intervals up to 5 min and at 1 min intervals up to a total erosion time of 15 min. SEM analysis was performed in lased samples (n=3). Data were statistically analysed by one-way ANOVA (p < 0.05) and Dunnett's post-hoc tests. **Results:** Calcium and phosphate release were significantly reduced by maximal 20% over time in samples irradiated with 0.4 J/cm² (200μs) at 450 Hz. Short-time reduction of calcium loss (≤ 1.5 min) could be also achieved by irradiation with 0.7 J/cm² (300μs) at 200 and 300 Hz. Both parameters revealed surface modification. **Conclusion:** Indeed a set of CO₂ laser parameters was found that could significantly reduce enamel mineral loss (20%) under *in vitro* erosive conditions. However, as all parameters caused also surface cracking, they are not recommended for clinical use.

Introduction

It has already been demonstrated that several wavelengths of a CO₂ laser may increase enamel acid resistance^{1,2}. However, most of the studies were conducted investigating the use of this laser for caries prevention and only a few for erosion prevention^{3,4}. In the latter studies, it was mostly investigated whether laser irradiation might improve the erosion-protective capability of fluorides rather than to analyse laser irradiation effects on the acid resistance of dental hard tissues *per se*. Thereby, different lasers with various parameters were used but no previous systematic screening was conducted to define appropriate laser parameters.

In previous experiments we have already shown that the low fluences (<1 J/cm²) when combined with short pulse durations (some tens of microseconds) may be effective in increasing enamel resistance to caries *in vitro*, while reducing the chances of thermal damage^{5,6}. This is possible because pulses of short duration increase the peak temperature caused at the surface but decrease the heat propagation to the interior of the tooth⁷. For example, irradiating enamel with the same fluence, and decreasing the pulse duration from 500 to 50 μs causes a 200°C difference in peak surface temperature⁸.

The mechanism through which laser irradiation decreases enamel solubility is apparently not related to melting and fusion. Actually most of the evidences point to temperature-related changes in enamel structure producing a more pure hydroxyapatite⁹. Indeed, recent findings showing decrease or complete carbonate elimination from the surface of enamel after irradiation with parameters causing high temperature increase support this theory^{8,10}. Simultaneously denaturation of organic matrix may also play a role in the observed effects¹¹ and the ideal surface temperature to cause these changes should be in the range between 600 and 900°C. Currently the studies which showed the best parameters for increasing enamel acid resistance either were conducted with industrial lasers, not available for clinical use, or showed parallel occurrence of side-effects, like surface cracking, or both^{1,5,12,13}. So there is still a need for finding conditions which could decrease enamel solubility with lasers already available for clinical use. This would shorten the time needed for laboratorial research becoming a reality for patient treatment. Recently, a new surgical laser has been introduced in the market that emits laser pulses with duration in the range of hundreds of microseconds, the range in which the CO₂ irradiation tends to be more safe and which was not available in earlier equipments. Therefore, the aim of the present study was to find CO₂ laser (10.6 μm) parameters from a new clinical laser to increase enamel resistance to erosive acid attack.

Materials and Methods

Sample preparation

Cylindrical enamel samples (3 mm in diameter, n = 270) were obtained from non-damaged crowns of freshly extracted bovine incisors, which were stored in 0.9% NaCl solution until used. The samples were embedded in acrylic resin blocks (6 mm in diameter, Paladur, Hereaus Kulzer, Germany). The labial surface of the specimens were ground flat and polished with water-cooled carborundum discs (1200, 2400 and 4000-grit, Water Proof Silicon carbide Paper, Stuers, Birmensdorf, Switzerland), thereby removing approximately 200 µm of the outermost layer as checked with a micrometer¹⁴. After polishing samples were sonicated for 30 s (Vitasonic II, Vita, Germany). Only samples presenting no cracks or structural defects were selected for the study and randomly allocated to the 12 treatment groups (each n = 20) and one control group (n = 30).

Laser Irradiation

Enamel irradiation was performed using a CO₂ laser emitting at 10.6 µm (Spectra Denta, Lutronic, Korea). Before the start of the experiments and to allow adequate determination of the energy densities, the beam diameter at 1/e² of the intensity level was determined through the knife-edge method. For all groups the zoom handpiece, at a fixed irradiation distance of 30 mm was used and determined a beam diameter of 2 mm at the sample surface. The zoom handpiece, allows the operator to choose between 5 different focus points and for this experiment the largest setting was used. Both time on and time off for the laser emission were fixed at 0.8 s. The energy emitted by the laser was checked during the whole irradiation period at a two-sample interval using an energy meter (Coherent Field Master GS + Detector LM45; Coherent, USA)¹⁵. As, to the best of our knowledge no study on erosion prevention has been published yet with this laser system, it was decided to start the investigations with the set of parameters recommended by the manufacturer. As these parameters showed in the pilot study no protection at all against enamel acid dissolution, new parameters were tested in order to search for the most adequate one. Criteria for inclusion were the absence of visible signs of ablation, carbonization and melting at the surface. Besides that, fluences below 1 J/cm² were preferred since previous studies have already shown their potential for increasing enamel acid resistance¹⁶. Detailed description of laser parameters is presented in Table 1.

Erosion experiment

Erosion of the lased samples (each group $n = 20$) and control specimens ($n = 30$) was performed in a small erosion chamber, which was described earlier by Wiegand et al. ¹⁴. Briefly, each sample was fixed in a brass jig, which allowed exposure of the enamel surface to a small erosion chamber of 2 mm in diameter and 0.3 mm in height. Hydrochloric acid (2.5 mmol/L, pH 2.6) was pumped at a flow rate 60 μ l/min from a reservoir outside the chamber into the space erosion chamber. The acid was collected via outlet pipes into wells of a microtiter plate. Eight chambers were each connected to a multichannel pump (Ismatec, Glattbrugg, Switzerland). In each run, seven test samples and 1 control sample were randomly assigned to the 8 chambers.

Samples were exposed to acid for a total of 15 min. For the first 5 min the acid was collected at consecutive 30 s intervals, then at 1 min intervals up to 15 min erosion.

Calcium and phosphate analysis

Release of calcium and phosphate into the acid was determined colorimetrically using the arsenazo III-method ^{17, 18} or the malachite green procedure ¹⁹, respectively.

Arsenazo-III reacts with calcium in an acid solution to form a blue-purple complex. The intensity developed is proportional to the calcium concentration. Absorption was determined at $\lambda = 650$ nm. For photometric determination of calcium, 10 μ l samples were used and mixed with 100 μ l reagent, which was composed of 100 mmol/l (imidazole buffer, pH 6.5) and 0.12 mmol/l arsenazo III (Fluitest, Ca-A-II, analyticon, Lichtenfels, Germany). Individual standard curves were obtained with a standardized calcium solution for determination of the calcium concentrations. Precision of the measurements was validated with standard solutions. The lowest standard of the calibration curve (0.4 nmol Ca/well) was considered as threshold for the detection limit of the procedure.

Malachite green reacts with phosphate to a coloured complex which can be determined at $\lambda = 650$ nm. For this purpose, 0.045 g malachite green dissolved in 100 ml aqua bidest. was admixed to 12.69 g ammonium molybdate, which was dissolved in 300 ml HCl (4 mol/l). The reagent was stirred for 30 min afterwards and filtered. For colorimetric phosphate determination, 5 μ l of each acid fraction was admixed to 200 μ l of the reagent. Individual

standard curves were obtained by admixing diluted samples of the standardized phosphate solution to the acid. The lowest standard of the calibration curve (0.117 nmol phosphate/well) was considered as threshold for precision.

Scanning electron microscopy (SEM)

Three samples each group were analysed by SEM (SUPRA 50VP, Carl Zeiss NTS GmbH, Oberkochen, Germany) at 5 kV after CO₂ laser irradiation. Samples were dehydrated using an ascending ethanol series up to 100%. The width of the microcracks was measured with the software Image J version 1.410 (National Institute of Health, USA).

Statistical analysis

Calcium and phosphate release of lased and control samples into the acid was measured in each acid fraction. Data were statistically analysed by one-way analysis of variance (ANOVA) at each time point. ANOVA was followed by Dunnett's post hoc tests to compare lased with control samples. Level of significance was set at $p \leq 0.05$.

Results

Calcium and phosphate release

The mean rate of calcium and phosphate release of control samples was stable over time and amounted to 0.362 ± 0.008 and 0.202 ± 0.006 $\mu\text{mol}/\text{cm}^2\text{min}$. For all test groups the means of calcium and phosphate loss ($\mu\text{mol}/\text{cm}^2$) at every 2 minutes are presented in tables 2 and 3.

Cumulative calcium and phosphate losses (mean % of control) of lased groups are presented in Fig 1 and 2. Within each group, coefficient of variation of calcium release varied between 9.1 and 26.4 at the different time points. Regarding the phosphate release, coefficient of variation in each group varied between 11.1 and 32.6 at the different time points.

Generally, the preventive effect of laser irradiation was limited. Calcium and phosphate release was reduced by only up to 20% compared to control, with only few groups reaching statistical significance ($p \leq 0.05$). Over time, calcium release was significantly reduced only in group 8, while groups 9 and 11 prevented calcium loss only in the first minute (Fig. 1). Group 9 at 1 and 1.5 min ($p=0.044$ and $p=0.047$) and group 11 at 0.5 min ($p=0.008$). Phosphate release was significantly reduced over time only in group 8 (Fig. 2). Group 11 showed only at 0.5 min significant less phosphate loss than the control ($p=0.031$) and groups 7 and 3 at 6 min ($p=0.049$ and $p=0.030$).

SEM analysis

At high magnification small nanocracks of less than 1 micrometer were observed at center of the irradiated surfaces, but with different extents. Samples of group 2, 3, 10 and 11 revealed only few cracks of less than 300 nm, while surfaces in groups 1, 4, 5 and 12 showed several nanocracks (500 to 700 nm). Most microcracks could be observed in group 6 to 9 (400 to 600 nm). A selection of characteristic lased surfaces is displayed in Fig 3

Discussion

In the present study pulse durations from 80 to 400 μs of a clinical CO_2 laser were tested for the first time with the aim of increasing enamel acid resistance. There was up to recently no clinical CO_2 laser in the market capable of emitting pulses of some hundreds of microseconds, therefore the conduction of clinical studies has been very limited to almost impossible²⁰. Also there is currently no protocol for a laser-treatment of patients at high-risk for erosion or caries, although the manufacturer has already included clinical recommendations of irradiation parameters in its treatment guidelines. Thus, as the increase of enamel acid resistance after CO_2 laser irradiations with low pulse durations ($< 100 \mu\text{s}$) has already been observed *in vitro* with the use of industrial lasers, and the manufacturer of this new laser system is already recommending preventive irradiation conditions to be used clinically, it was hypothesized that a high increase of enamel acid resistance could be obtained also with this new clinical device^{1, 5, 21-23}. However, this hypothesis was not totally confirmed, since the maximum reduction of calcium and phosphate loss was of only 20%, which is much less than the already observed 70-81% caries inhibition and the 97% reduction of enamel softening²².

Nevertheless, it was possible to obtain some insights about how the different laser parameters may influence the increase or decrease of enamel acid solubility. For the pulse durations, which resulted in the highest inhibitions, namely 200 and 300 μs , it is interesting to observe that in both cases, with the increase of the frequency there was a slight increase of enamel acid resistance. This increase was indeed small (5% reduction of calcium loss when the frequency was increased from 400 to 450 Hz, in G7 and G8, and from 250 to 300 Hz, in G10 and G11) and probably for this study irrelevant, however as a similar effect has been observed in other studies⁷, it seems worthy to note this tendency as it may contribute to better understanding of the laser-tissue interaction in future investigations.

Another interesting tendency to be observed is that for all parameters tested a decrease of the effect with the time is seen; and this probably indicates the elimination of the laser-modified layer. For the parameters, which caused initially a decrease of the mineral loss, there is with the passage of the time a slight increase in the quantity of Ca and PO_4 released. On the other hand, for the parameters which caused initially a slight increase of the mineral loss (higher than the control) the opposite occurs and a decrease is observed as the time passes. Although these differences in the effect over time were also not statistically significant, it is interesting to note it since these gradients of effect in the tissue have been well-described by Nelson et al. 1986 and should be better investigated in further studies²⁴.

The increase of enamel acid resistance after laser irradiation is strongly related to the temperature increase caused at the tissue. When enamel is heated to a specific temperature range (600-900°C) not only less soluble hydroxyapatite may be formed but also elimination of mineral impurities, as carbonate, and changes in the organic matrix may occur. However, the positive modification of the tooth mineral solubility is very sensible and depend on strict heating and cooling conditions. As during the laser irradiation the tooth is not equally heated at the surface and inner layers, the modifications in solubility in inwards direction are not the same. Therefore the degree of acid resistance of lased-enamel occur in gradients and it is possible that over a layer of more acid-resistant enamel, less resistant ones are present, accordingly to the distance from the surface 9, 24.

Although the increase of temperature can be very positive for enamel solubility, it may also have a negative side. This means that if the temperature is not increased only for a short period of time (few micro-fractions of a second) heat accumulation can happen and cause ablation, melting or cracking of tissue 25. Such kind of unwanted effects were also observed here. Besides the significant increase of enamel resistance to erosion, the laser parameters tested in the present study have shown, under scanning electron microscopy and higher magnification, some surface modification. Surface nanocracks of less than 1 µm width were observed in the samples of almost all the groups. As already expected from previous studies ^{10, 12}, the groups with the lowest pulse durations and lowest energy density caused the lowest amount of morphological changes, but caused at the same time a limited increase of enamel acid resistance.

In the present study a relative strong acid attack was reproduced. The erosion model using hydrochloric acid (pH 2.6) simulates the clinical situation of patients suffering from gastroesophageal reflux and frequent vomiting (Bulimia), which cause gastric acid penetration into the oral cavity. Besides, the use of an erosion chamber had two important advantages. The first is that it allowed constant acid flow over the samples, thus preventing acid saturation, normally observed in static conditions; and the second is the possibility of allowing constant acid attack for 15 min, which provides some indications about the duration of the protective effects ¹⁴. The limitation, on the other hand, is the absence of any remineralisation solution to simulate the saliva counterbalance on enamel dissolution. However, considering that it is a well-established model which provides standardised and reproducible erosive conditions, it fulfilled the necessities of this initial and explorative study 26. Anyway, it must also be kept in mind that this was a a relative strong acid attack and that under clinical conditions an acid challenge results in pH fall below the critical level only for 2 min at the tooth surfaces 27. These surfaces are additionally normally protected with a protective barrier, the acquired pellicle, and therefore under clinical conditions probably less

enamel dissolution should be observed. Even though the maximum effect achieved by the best laser condition was not very high, this effect was in the same range as the protection achieved by several types of fluoride treatment in the same erosion model¹⁴. Fluoride gel (AmF/NaF, 1,25% F) and tetrafluoride solutions like TiF₄ (0.4 and 1 %), ZrF₄ (0.4 and 1 %), HF₄ (0.4 and 1 %) caused also around 20% erosion reduction¹⁴. Higher protection was observed by Yu et al. 2010, but in samples previously covered with acquired salivary pellicle, formed *in situ*²⁸. As the pellicle is known to act as barrier to acid diffusion and provide additional protective effect against erosion, it cannot be stated that the high reduction observed in that study was only caused by fluoride application. Nevertheless other fluoride compounds have already shown higher erosive resistance in other erosion models²⁹.

Reduction of carious and/or erosive tooth dissolution has been also observed after enamel irradiation with other types of lasers, such as the diode, Nd:YAG and erbium lasers³⁰⁻³². However, in most of these studies significant increase of acid resistance has been only obtained when the irradiation was combined with fluoride compounds. In this case significant reduction as compared to non-treated controls has been observed for the combination of Nd:YAG laser with titanium tetrafluoride (TiF₄) solution³³ and with acidulated phosphate fluoride (APF)^{30, 34, 35}. Additionally, increase of fluoride uptake at the enamel surface has been also observed for the combination of diode laser irradiation with neutral sodium fluoride (NaF)³⁶. However, none of them though showed increased enamel resistance to acid solubility after solely laser irradiation, as observed in the present study.

The recommendation of the laser manufacturer in its treatment guidelines provided together with the laser equipment may be misleading for several clinicians. Considering that all the laser conditions tested here caused the occurrence of nanocracks at the surface, a clinical application of this laser in erosion prevention would only make sense in case its combination with fluoride products would drastically increase fluoride retention or form a metal-containing coating layer highly bound to enamel and capable of sealing the nanocracks caused by the irradiation^{28, 29, 37}. However this hypothesis must be investigated in future studies.

Under the conditions of this study, the maximum statistically significant increase of enamel resistance to erosive mineral loss was obtained after CO₂ laser (10.6 μm) irradiation at 0.4 J/cm² (200 μs, 450 Hz) and was of 20%. As the irradiation also caused side-effects at the surface, even these parameters cannot be recommended for clinical use.

Conflict of interest statement

The authors declare they have no conflict of interest.

Figure Legends

Figure 1

Cumulative calcium loss (mean, % of control) of enamel in the differently lased groups. Calcium release was significantly reduced in group 8 (all time points except $t = 2.5$ min, $t = 3.5$ min, $t = 4$ min, $t = 5$ min, and $t = 10$ min), group 9 (time points $t = 1$ min, $t = 1.5$ min) and group 11 ($t = 0.5$ min).

Figure 2

Cumulative phosphate loss (mean, % of control) of enamel in the differently lased groups. Phosphate release was significantly reduced in group 8 at $t = 0.5$ min, $t = 1$ min, $t = 2$ min, $t = 2.5$ min, $t = 3.5$ min, $t = 4.5$ min, $t = 5$ min and $t = 6$ min. At $t = 0.5$ min phosphate release was also significantly reduced in group 11, and at $t = 6$ min in groups 3 and 7.

Figure 3

Characteristic SEM pictures of control and lased samples (10000x magnification, bar: 2 μm).

- a) control without any surface alterations
- b) few nanocracks (exemplary sample from group 2) having 259 to 264 nm of width
- c) several nanocracks (exemplary sample from group 1) having 510 to 678 nm of width
- d) most nanocracks (exemplary sample from group 8) having 423 to 579 nm of width

References

1. Featherstone, J.D.B., Barrett-Vespone, N.A., Fried, D., Kantorowitz, Z., and Seka, W. (1998). CO₂ laser inhibition of artificial caries-like lesion progression in dental enamel. *J. Dent. Res.* 77, 1397-1403.
2. Esteves-Oliveira, M., Zezell, D.M., Meister, J., et al. (2009). CO₂ Laser (10.6 μm) parameters for caries prevention in dental enamel. *Caries Res.* 43, 261-268.
3. Wiegand, A., Magalhaes, A.C., Navarro, R.S., et al. (2010). Effect of titanium tetrafluoride and amine fluoride treatment combined with carbon dioxide laser irradiation on enamel and dentin erosion. *Photomed. Laser Surg.* 28, 219-226.
4. Steiner-Oliveira, C., Nobre-dos-Santos, M., Zero, D.T., Eckert, G., and Hara, A.T. (2010). Effect of a pulsed CO₂ laser and fluoride on the prevention of enamel and dentine erosion. *Arch. Oral Biol.* 55, 127-133.
5. Esteves-Oliveira, M., Zezell, D.M., Meister, J., et al. (2009). CO₂ Laser (10.6 μm) parameters for caries prevention in dental enamel. *Caries Res.* 43, 261-268.
6. Esteves-Oliveira, M., Apel, C., Gutknecht, N., et al. (2008). Low-fluence CO₂ laser irradiation decreases enamel solubility. *Laser Phys.* 18, 478-485.
7. Fried, D., Seka, W., Glena, R.E., and Featherstone, J.D.B. (1996). Thermal response of hard dental tissues to 9- through 11-μm CO₂-laser irradiation. *Opt. Eng.* 35, 1976-1984.
8. Fried, D., Murray, M.W., Featherstone, J.D.B., et al. (1999). Dental hard tissue modification and removal using sealed TEA lasers operating at λ=9.6 μm and 10.6 μm. in: *Lasers in Dentistry V. Proceedings of the SPIE Meeting*. San Jose: Bellingham, pp. 196-203.
9. Fowler, B.O., and Kuroda, S. (1986). Changes in heated and in laser-irradiated human tooth enamel and their probable effects on solubility. *Calcif. Tissue Int.* 38, 197-208.
10. Zuerlein, M.J., Fried, D., and Featherstone, J.D.B. (1999). Modeling the modification depth of carbon dioxide laser-treated dental enamel. *Lasers Surg. Med.* 25, 335-347.
11. Hsu, C.Y., Jordan, T.H., Dederich, D.N., and Wefel, J.S. (2000). Effects of low-energy CO₂ laser irradiation and the organic matrix on inhibition of enamel demineralization. *J.Dent. Res.* 79, 1725-1730.
12. McCormack, S.M., Fried, D., Featherstone, J.D.B., Glena, R.E., and Seka, W. (1995). Scanning electron microscope observations of CO₂ laser effects on dental enamel. *J. Dent. Res.* 74, 1702-1708.
13. Rodrigues, L.K., Nobre Dos Santos, M., and Featherstone, J.D. (2006). In situ mineral loss inhibition by CO₂ laser and fluoride. *J. Dent. Res.* 85, 617-621.
14. Wiegand, A., Meier, W., Sutter, E., et al. (2008). Protective effect of different tetrafluorides on erosion of pellicle-free and pellicle-covered enamel and dentine. *Caries Res.* 42, 247-254.

15. Esteves-Oliveira, M., Zezell, D.M., Ana, P.A., Yekta, S.S., Lampert, F., and Eduardo, C.P. (2011). Dentine caries inhibition through CO₂ laser (10.6µm) irradiation and fluoride application, in vitro. *Arch. Oral Biol.* 56, 533-539.
16. Gerard, D.E., Fried, D., Featherstone, J.D., and Nancollas, G.H. (2005). Influence of laser irradiation on the constant composition kinetics of enamel dissolution. *Caries Res.* 39, 387-392.
17. Attin, T., Becker, K., Hannig, C., Buchalla, W., and Hilgers, R. (2005). Method to detect minimal amounts of calcium dissolved in acidic solutions. *Caries Res.* 39, 432-436.
18. Hannig, C., Becker, K., Yankeu-Ngalene, V.E., and Attin, T. (2008). Applicability of common methods for short time erosion analysis in vitro. *Oral Health Prev. Dent.* 6, 239-248.
19. Attin, T., Becker, K., Hannig, C., Buchalla, W., and Wiegand, A. (2005). Suitability of a malachite green procedure to detect minimal amounts of phosphate dissolved in acidic solutions. *Clin. Oral Investig.* 9, 203-207.
20. Rechmann, P., Fried, D., Le, C.Q., et al. (2008). Inhibition of caries in vital teeth by CO₂ laser treatment. in: *Lasers in Dentistry XIV. Proceedings of the SPIE Meeting.* San Jose, CA, USA: SPIE, pp. 684307-684307.
21. Kantorowitz, Z., Featherstone, J.D.B., and Fried, D. (1998). Caries prevention by CO₂ laser treatment: Dependency on the number of pulses used. *J. Am. Dent. Assoc.* 129, 585-591.
22. Esteves-Oliveira, M., Pasaporti, C., Heussen, N., Eduardo, C.P., Lampert, F., and Apel, C. (2011). Rehardening of acid-softened enamel and prevention of enamel softening through CO₂ laser irradiation. *J. Dent.* 39, 414-421.
23. Esteves-Oliveira, M., Pasaporti, C., Heussen, N., Eduardo, C.P., Lampert, F., and Apel, C. (2011). Prevention of toothbrushing abrasion of acid-softened enamel by CO₂ laser irradiation. *J. Dent.* 39, 604-611.
24. Nelson, D.G., Shariati, M., Glena, R., Shields, C.P., and Featherstone, J.D. (1986). Effect of pulsed low energy infrared laser irradiation on artificial caries-like lesion formation. *Caries Res.* 20, 289-299.
25. Staninec, M., Meshkin, N., Manesh, S.K., Ritchie, R.O., and Fried, D. (2009). Weakening of dentin from cracks resulting from laser irradiation. *Dent. Mater.* 25, 520-525.
26. Shellis, R.P., Ganss, C., Ren, Y., Zero, D.T., and Lussi, A. (2011). Methodology and models in erosion research: discussion and conclusions. *Caries Res.* 45 Suppl 1, 69-77.
27. Millward, A., Shaw, L., Harrington, E., and Smith, A.J. (1997). Continuous monitoring of salivary flow rate and pH at the surface of the dentition following consumption of acidic beverages. *Caries Res.* 31, 44-49.
28. Yu, H., Attin, T., Wiegand, A., and Buchalla, W. (2010). Effects of various fluoride solutions on enamel erosion in vitro. *Caries Res.* 44, 390-401.
29. Schlueter, N., Hardt, M., Lussi, A., Engelmann, F., Klimek, J., and Ganss, C. (2009). Tin-containing fluoride solutions as anti-erosive agents in enamel: an in vitro tin-

- uptake, tissue-loss, and scanning electron micrograph study. *Eur. J. Oral Sci.* 117, 427-434.
30. Zezell, D.M., Boari, H.G., Ana, P.A., Eduardo Cde, P., and Powell, G.L. (2009). Nd:YAG laser in caries prevention: a clinical trial. *Lasers Surg. Med.* 41, 31-35.
 31. Naylor, F., Aranha, A.C., Eduardo Cde, P., Arana-Chavez, V.E., and Sobral, M.A. (2006). Micromorphological analysis of dentinal structure after irradiation with Nd:YAG laser and immersion in acidic beverages. *Photomed. Laser Surg.* 24, 745-752.
 32. De Sant'Anna, G.R., Paleari, G.S., Duarte, D.A., Brugnera, A., Jr., and Soares, C.P. (2007). Surface morphology of sound deciduous tooth enamel after application of a photo-absorbing cream and infrared low-level laser irradiation: an in vitro scanning electron microscopy study. *Photomed. Laser Surg.* 25, 500-507.
 33. Magalhaes, A.C., Romanelli, A.C., Rios, D., et al. (2011). Effect of a single application of TiF₄ and NaF varnishes and solutions combined with Nd:YAG laser irradiation on enamel erosion in vitro. *Photomed. Laser Surg.* 29, 537-544.
 34. Rios, D., Magalhaes, A.C., Machado, M.A., et al. (2009). In vitro evaluation of enamel erosion after Nd:YAG laser irradiation and fluoride application. *Photomed. Laser Surg.* 27, 743-747.
 35. Sobral, M.A., Lachowski, K.M., de Rossi, W., Braga, S.R., and Ramalho, K.M. (2009). Effect of Nd:YAG laser and acidulated phosphate fluoride on bovine and human enamel submitted to erosion/abrasion or erosion only: an in vitro preliminary study. *Photomed. Laser Surg.* 27, 709-713.
 36. de Sant'anna, G.R., dos Santos, E.A., Soares, L.E., et al. (2009). Dental enamel irradiated with infrared diode laser and photoabsorbing cream: Part 1 -- FT-Raman Study. *Photomed. Laser Surg.* 27, 499-507.
 37. Meurman, J.H., Hemmerle, J., Voegel, J.C., Rauhamaa-Makinen, R., and Luomanen, M. (1997). Transformation of hydroxyapatite to fluorapatite by irradiation with high-energy CO₂ laser. *Caries Res.* 31, 397-400.

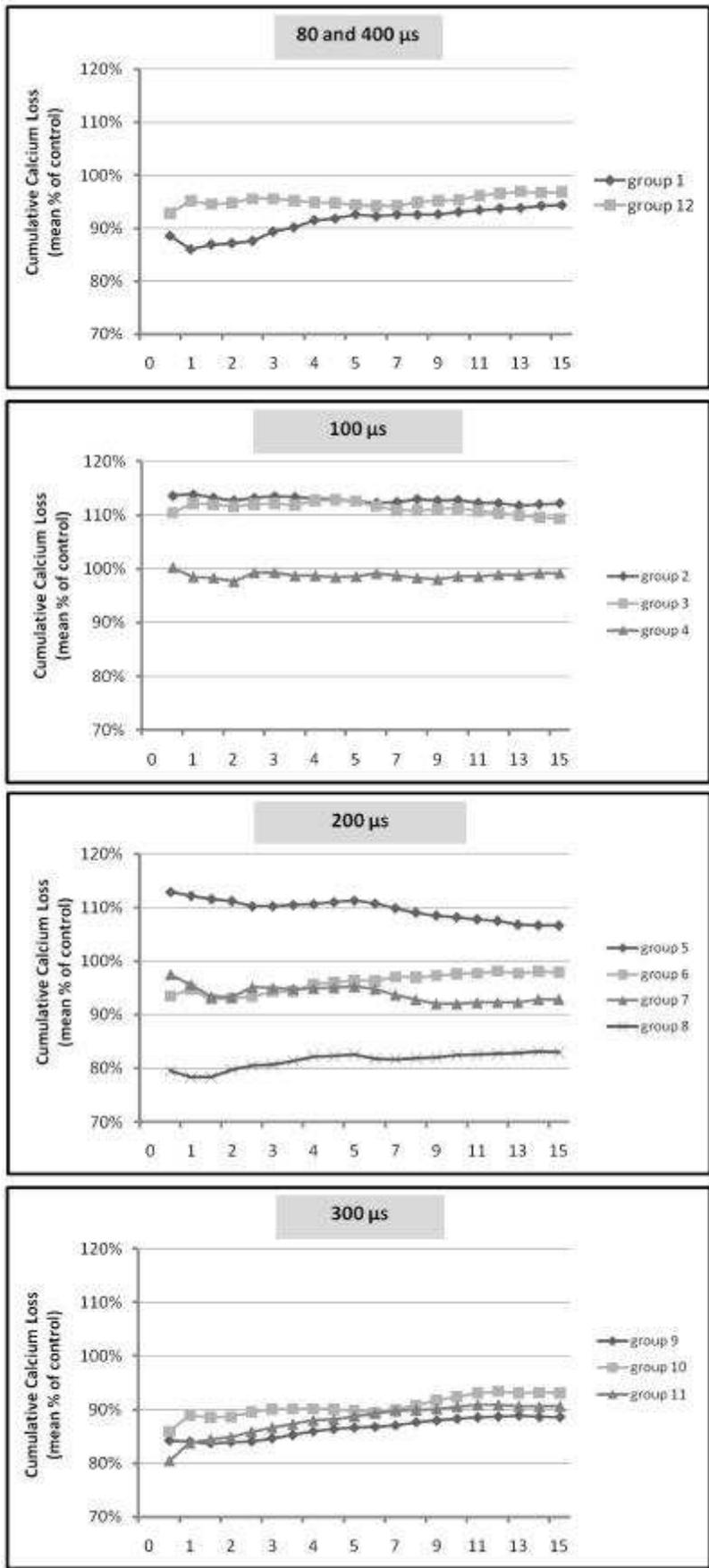


Figure 1

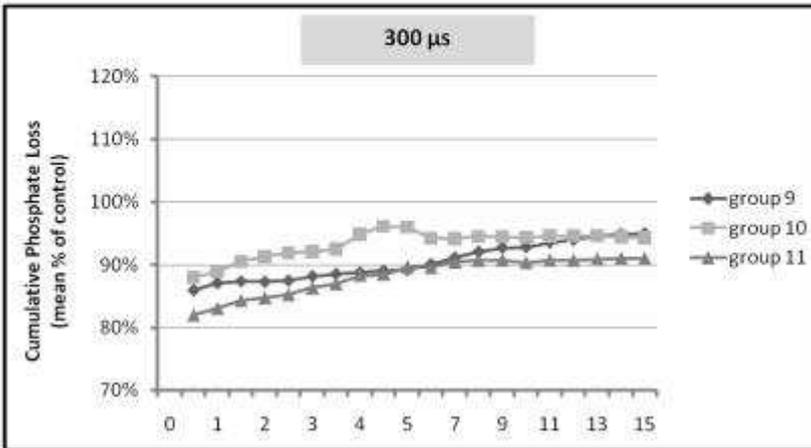
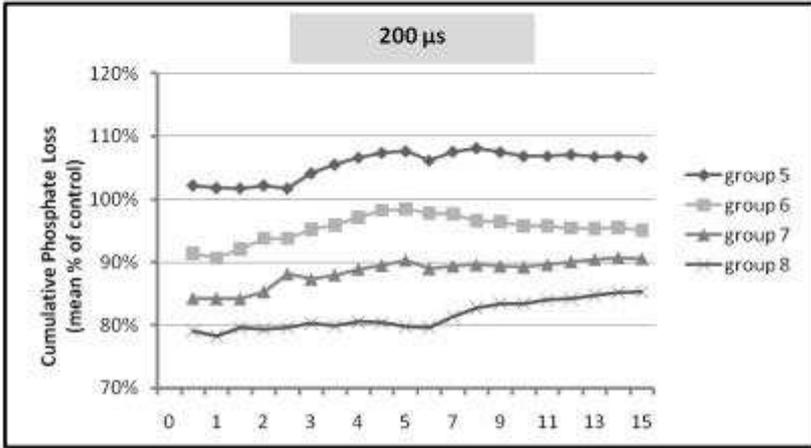
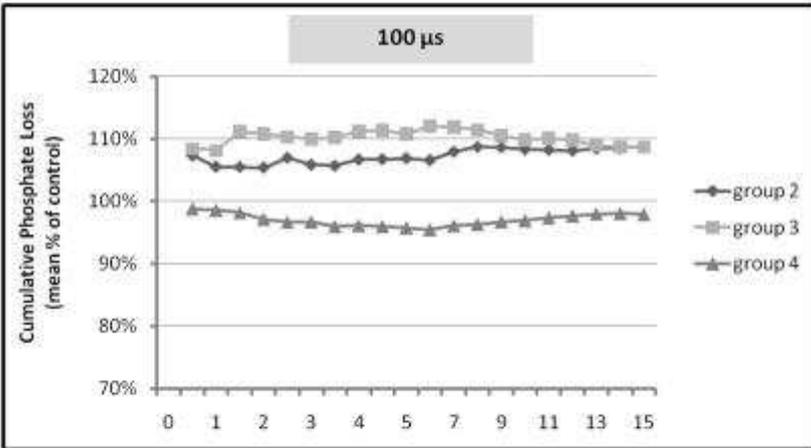
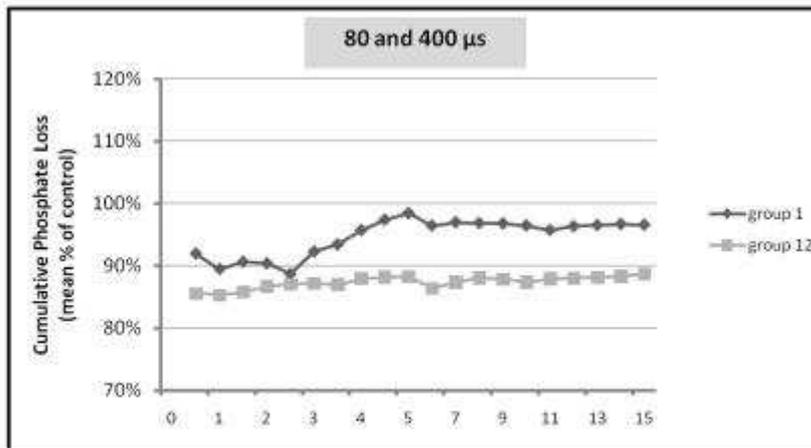


Figure 2

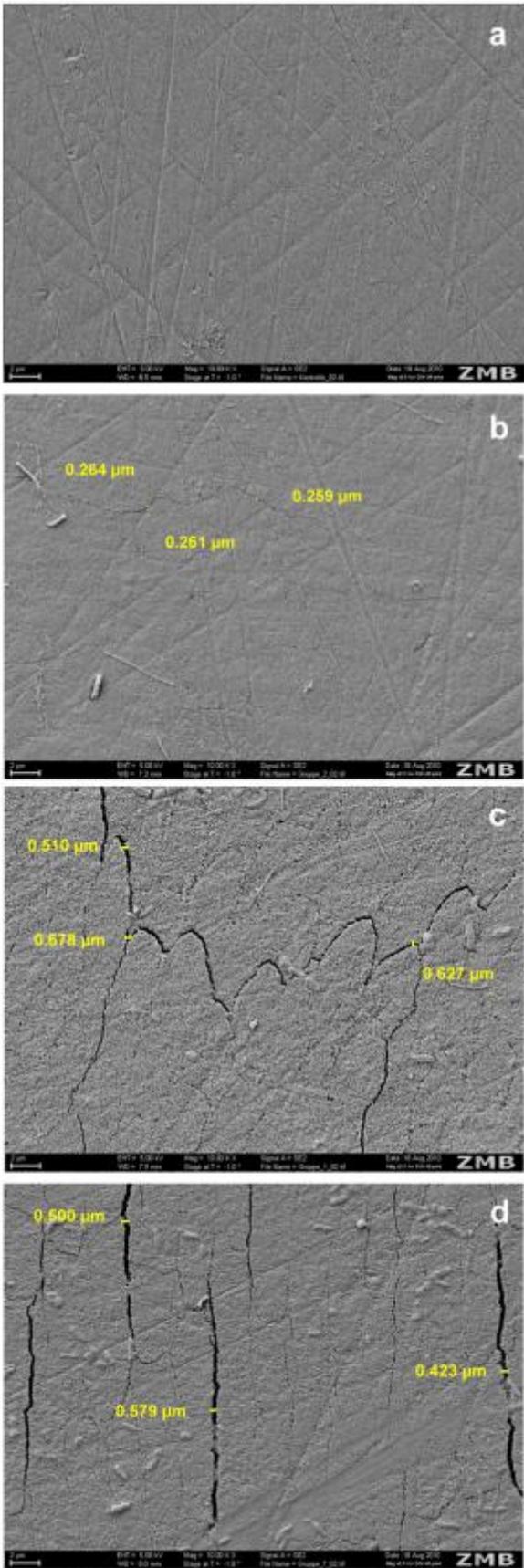


Figure 3