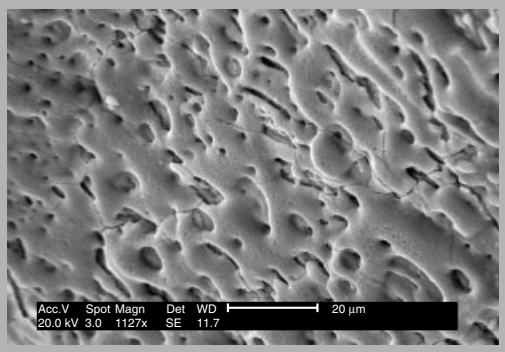
Abstract: Background: The objective was to evaluate the morphology of enamel and dentin irradiated with Er:YAG (2.94 μm) and CO_2 (9.6 μm) lasers. Methods: Six groups were evaluated: G1 – CO_2 irradiated enamel (3 W); G2 – CO_2 irradiated dentin (3 W); G3 – CO_2 irradiated enamel (7 W); G4 – CO_2 irradiated dentin (7 W); G5 – Er:YAG irradiated enamel (0.16 W); G6 – Er:YAG irradiated dentin (0.16 W). Results: The morphological pattern of Er:YAG laser irradiated enamel and dentin has a rough aspect with a clear exposition of the prisms and dentinal tubules. The melted surfaces covering the CO_2 laser irradiated enamel and dentin, occlude the dentinal tubules and the enamel prisms. Conclusion: The rough pattern after Er:YAG laser irradiation, which originates from the micro-explosion of water, does not occlude the dentinal tubules, whereas the surface morphology after CO_2 laser irradiation, which originated from the temperature rise above hydroxyapatite melting point, shows dentinal tubules occlusion and tissue melting. Clinical implications: These changes influence the tissue properties such as increase of the enamel acid resistance or decrease the bond strength between the tissue and composite resin.



Dentin surface after CO_2 laser irradiation (9.6 μm, 350 mJ, 20 Hz, 495 J/cm^2, 7 W); the melted surface is more homogeneous and totally occludes the dental tubules

© 2005 by Astro Ltd.
Published exclusively by WILEY-VCH Verlag GmbH & Co. KGaA

Morphological evaluation of enamel and dentin irradiated with 9.6 μm CO_2 and 2.94 μm Er:YAG lasers

T.M. Marraccini, [1] *L. Bachmann,* [2,*] *H.A. Wigdor,* [3] *J.T. Walsh Jr.,* [4] *A. Stabholtz,* [5] *and D.M. Zezell* [1]

[1] Centro de Lasers e Aplicações, Instituto de Pesquisas Energéticas e Nucleares, 2242, Av. Lineu Prestes, São Paulo 05508-900, Brazil
[2] Departamento de Física e Matemática, Faculdade de Filosofia, Ciências e Letras de Ribeirão Preto, Universidade de São Paulo, 3900, Av. dos Bandeirantes, Ribeirão Preto, São Paulo 14040-901, Brazil
[3] Chairman Department of Dentistry, Advocate, Illinois Masonic Medical Center, 811, W Wellington 60657, Chicago Illinois, USA
[4] Biomedical Engineering Department, Northwestern University, 2145, Sheridan Road Evanston, IL 60208-3107, USA
[5] Department of Endodontics, The Hebrew University, Hadassah, School of Dental Medicine P.O.Box 12272, Jerusalem 91120, Israel

Received: 5 July 2005, Accepted: 12 July 2005
Published online: 22 July 2005

Key words: erbium laser; carbon dioxide laser; hard dental tissues; scanning electron microscopy

PACS: 87.64.Ee, 87.19.Rr, 87.68+z

1. Introduction

Enamel and dentin removal can be achieved using lasers with wavelengths that are strongly absorbed by these tissues. In the infrared, the strongest absorption bands occur in the 2-3 μm and 9-11 μm regions [1]. These two regions are readily accessible by holmium [2], erbium [3,4] and CO_2 [5] lasers systems. The holmium and erbium laser wavelength emission depends on the host: Ho:YAG at 2.1 μm, Ho:YLF at 2.065 μm Er:YAP at 2.73 μm, Er:YSGG at 2.79 μm, Er:YLF at 2.81 μm and Er:YAG at 2.94 μm. The carbon dioxide laser has primary emission at: 9.3 μm, 9.6 μm, 10.3 μm, and 10.6 μm.

The mineral matrix of the enamel and dentin is composed of crystals of hydroxyapatite $Ca_5(PO_4)_3OH$, with carbonate radicals substituting for the phosphate and hy-

* Corresponding author: e-mail: bachmann@ffclrp.usp.br

© 2005 by Astro Ltd.
Published exclusively by WILEY-VCH Verlag GmbH & Co. KGaA

	Enamel		Dentin	
	α, cm^{-1}	τ, μs	α, cm^{-1}	τ, μs
CO_2 - 9.6 μm	8000	1	6500	3.3
Er:YAG - 2.94 μm	800	90	2200	28

Table 1 Absorption coefficient (α) and associated thermal relaxation time (τ) of the enamel and dentin at 2.94 μm and 9.6 μm [11–13]

droxyl radicals. The enamel organic matrix is composed of proteins, lipids, sugars and citrates; while the dentin organic matrix is mainly composed of collagen and a small fraction of other proteins [1]. Besides the two described matrixes, water [6] and other trace chemical elements [7] are present in enamel and dentin. Enamel is 95.5 wt% inorganic material, 0.5 wt% organic material and 4 wt% water while the dentin is 69.3 wt% inorganic material, 17.5 wt% organic material and 13.2 wt% water. The tissue chemical composition results in several infrared bands in the absorption spectra [1]. The two strongest absorption bands are associated with water (2-3 μm) and the phosphate radical (9-11 μm). The laser wavelengths 2.94 μm, from the Er:YAG laser, and 9.6 μm, from the CO_2 laser, coincident with these absorption bands.

In order to compare the laser-tissue interaction of the Er:YAG laser at 2.94 μm and CO_2 laser at 9.6 μm, we list in Table 1 the absorption coefficient and thermal relaxation time for enamel and dentin [8–10].

The Er:YAG and CO_2 laser energy absorbed by the tissue produces a significant temperature rise at the surface [11]. This temperature depends on the irradiation conditions as well as the tissue parameters (absorption coefficient, thermal diffusivity, etc.) The material ablated by the laser energy takes away a significant fraction of the deposited energy and only a fraction of the incident laser energy remains to heat the non-ablated tissue.

CO_2 - 9.6 μm laser irradiation of enamel with 6 J/cm^2, 100-μs-long pulses generates a temperature rise of $\sim$1000 °C; an irradiation with 10 J/cm^2 results in a temperature rise above 1200 °C [11]. Er:YAG laser irradiation of enamel with 7 J/cm^2, 150-μs-long pulses produces a temperature rise of $\sim$300 °C; 9 J/cm^2 yields a surface temperature rise of $\sim$1000 °C.

During tissue irradiation, when the optical energy is converted into heat, it can diffuse to underlying soft tissues, in which case necrosis can occur. In order to avoid thermal damage to the pulp as well as periodontal tissues, safe irradiation parameters must be used. The determination of safe Er:YAG and CO_2 - 9.6 μm laser irradiation parameters [12,13] was done previously and the applicability in clinical practice was shown [3–5].

Given that tissue removal with an Er:YAG laser at 2.94 μm and a CO_2 laser at 9.6 μm, involve different primary absorbers [11] with different absorption cross-sections, the thermal gradient produced by each laser is different. Consequently one might expect to see a difference in the denaturation of the dentin collagen matrix and the change in enamel prismatic morphology produced by these two lasers systems. Such differences might affect the bond strength between the tissue and composite resin.

The objective of this study was to evaluate the morphology of enamel and dentin irradiated with an Er:YAG laser emitting at 2.94 μm, and a CO_2 laser emitting at 9.6 μm, with the expectation that observed differences in morphology would help explain differences in bond strength and ultimately lead to the development of improved restorative materials.

2. Materials and methods

Twelve bovine incisors teeth were selected for this work; all teeth were free of hypoplastic areas, cracks, irregularities in the enamel morphology or other dental pathologies. The teeth were cleaned, had their crowns separated from their roots and, were divided in six groups:

- Group 1 – Enamel irradiated with CO_2 laser (150 mJ, 20 Hz, 212.2 J/cm^2, 3 W);
- Group 2 – Dentin irradiated with CO_2 laser (150 mJ, 20 Hz, 212.2 J/cm^2, 3 W);
- Group 3 – Enamel irradiated with CO_2 laser (350 mJ, 20 Hz, 495 J/cm^2, 7 W);
- Group 4 – Dentin irradiated with CO_2 laser (350 mJ, 20 Hz, 495 J/cm^2, 7 W);
- Group 5 – Enamel irradiated with Er:YAG laser (80 mJ, 2 Hz, 25.7 J/cm^2, 0.16 W);
- Group 6 – Dentin irradiated with Er:YAG laser (80 mJ, 2 Hz, 25.7 J/cm^2, 0.16 W).

For irradiation, an Er:YAG laser (Kavo Key II, Kavo Co., Biberach, Germany) with emission wavelength at 2.94 μm and a CO_2 laser (Opus96, Opus Dent, Tel Aviv, Israel) with emission at 9.6 μm were used. In Table 2 the beam characteristics and irradiation parameters for the two laser systems are summarized.

For morphological analysis a scanning electron microscope (XL30, Philips, Eindhover, Holland) was used. Samples were dehydrated in alcohol solutions of increasing concentrations (50, 75, 90, and 100%) during 30 minutes for each concentration and sputtered with gold. All dehydrated gold covered samples where kept in a dry atmosphere until the morphology evaluation.

3. Results

The enamel and dentin irradiated with 3 W power from the CO_2 laser and 0.16 W from the Er:YAG laser did not result in a cavity; while the 7 W CO_2 laser produced a cavity depth of about 1.5 mm.

Neither the CO_2 nor the Er:YAG laser produced cracks or other undesirable flaws in the tissue surface. On the left side of Fig. 1 and Fig. 2 one sees the non-irradiated

© 2005 by Astro Ltd.
Published exclusively by WILEY-VCH Verlag GmbH & Co. KGaA

	Emission wavelength	Pulse duration	Beam diameter	Energy per pulse	Repetition rate	Exposure time	Fluence	Average power
CO_2	9.6 μm	60 μs	0.3 mm	150 mJ	20 Hz	4 s	212 J/cm^2	3 W
				350 mJ	20 Hz	60 s	495 J/cm^2	7 W
Er:YAG	2.94 μm	200-500 μs	0.63 mm	80 mJ	2 Hz	60 s	25.7 J/cm^2	0.16 W

Table 2 Laser beam characteristics and irradiation parameter for the erbium and CO_2 laser systems

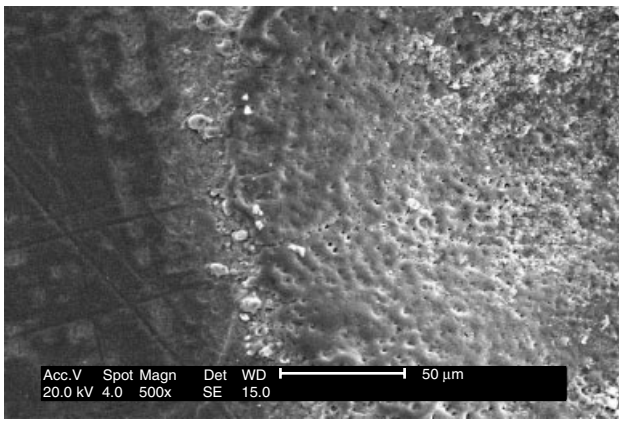


Figure 1 The natural enamel is observed in the left side of the figure and the CO_2 laser irradiated surface (9.6 μm, 150 mJ, 20 Hz, 212.2 J/cm^2, 3 W) is observed in the right side

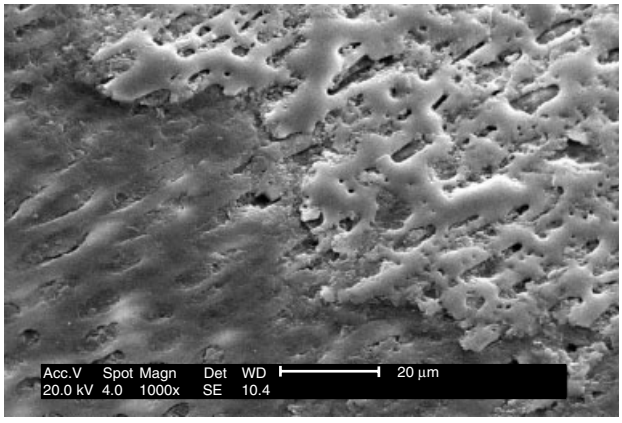


Figure 2 The natural dentin is observed in the left side of the figure and the CO_2 laser irradiated surface (9.6 μm, 150 mJ, 20 Hz, 212.2 J/cm^2, 3 W) is observed in the right side; a well-defined limit between the irradiated and natural dentin can be visualized

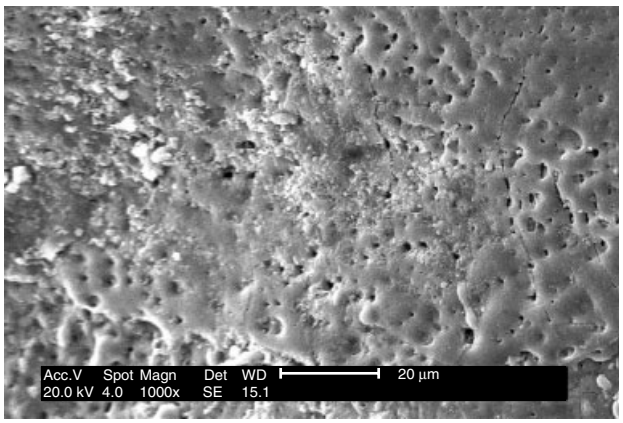


Figure 3 Enamel surface after CO_2 laser irradiation (9.6 μm, 150 mJ, 20 Hz, 212.2 J/cm^2, 3 W); a melted surface is formed after the irradiation and the prismatic structure of the enamel is not seen

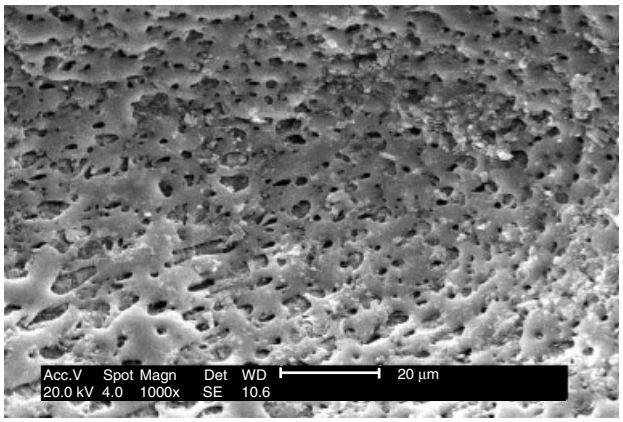


Figure 4 Dentin surface after CO_2 laser irradiation (9.6 μm, 150 mJ, 20 Hz, 212.2 J/cm^2, 3 W); the melted surface partially occludes the dental tubules

enamel and dentin respectively. The right sides of the figures show tissue that was irradiated with the 3 W CO_2. A well-defined boundary between the irradiated tissue (melted surface) and non-irradiated tissue can be observed. In Figs. 3 and 4 the melted surface after the CO_2 laser irradiation with 3 W is observed.

Both the CO_2 laser irradiated enamel (Figs. 3 and 5) and dentin (Figs. 4 and 6) with both powers show a melt pattern. These melted tissues cover the prisms structure in the enamel and occlude the dentinal tubules.

The 0.16 W Er:YAG laser irradiated enamel (Fig. 7) looks like a "ruptured surface", i.e., a surface without

© 2005 by Astro Ltd.
Published exclusively by WILEY-VCH Verlag GmbH & Co. KGaA

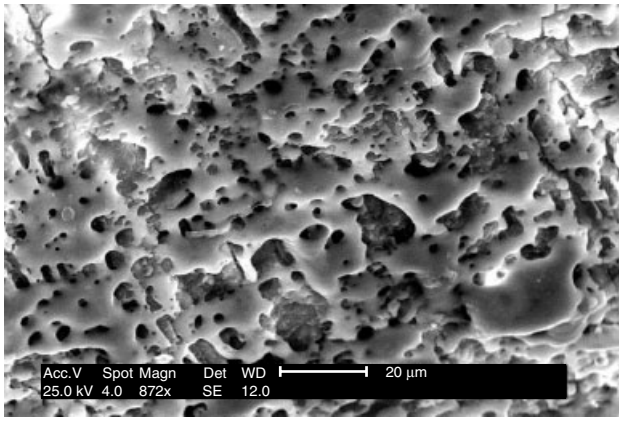


Figure 5 Enamel surface after CO_2 laser irradiation (9.6 μm, 350 mJ, 20 Hz, 495 J/cm^2, 7 W); the melted surface cover the prismatic structure of the enamel

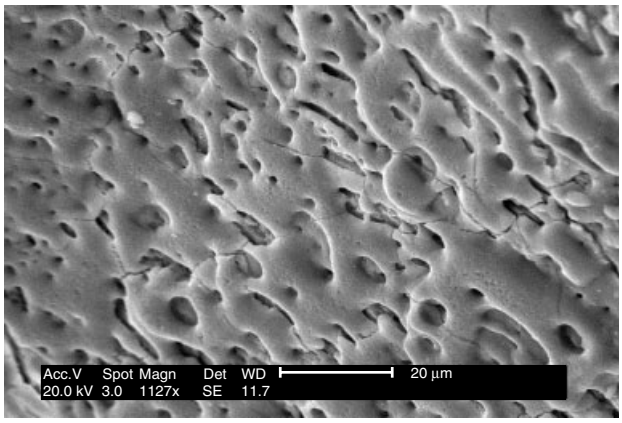


Figure 6 Dentin surface after CO_2 laser irradiation (9.6 μm, 350 mJ, 20 Hz, 495 J/cm^2, 7 W); the melted surface is more homogeneous and totally occludes the dental tubules

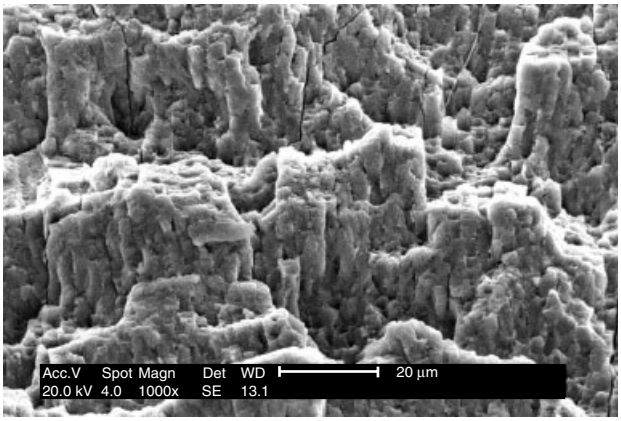


Figure 7 Enamel surface after Er:YAG laser irradiation (2.94 μm, 80 mJ, 2 Hz, 25.7 J/cm^2, 0.16 W); the morphological pattern after the irradiation shows a rough surface and the prismatic structure typical of enamel

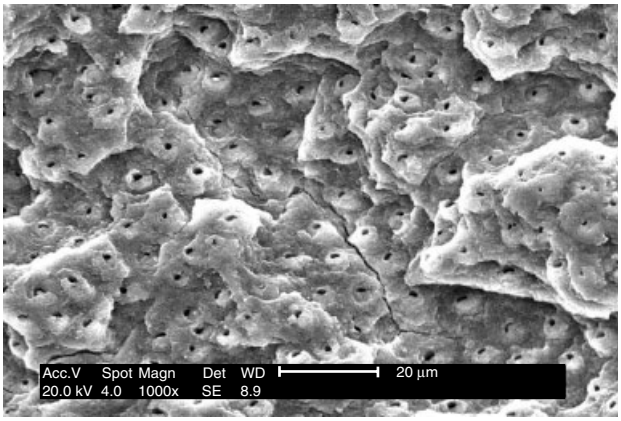


Figure 8 Dentin surface after Er:YAG laser irradiation (2.94 μm, 80 mJ, 2 Hz, 25.7 J/cm^2, 0.16 W); the morphological pattern after the irradiation shows a rough surface and open dentinal tubules

melted tissue and with a visible prism structure. The Er:YAG laser irradiated dentin (figure 8) has a rough surface without melting; open dentinal tubules are also observed.

4. Discussion

The morphological features after laser irradiation originated from the different tissue absorption characteristics. The Er:YAG laser has a wavelength emission resonant with the vibration energy of the water molecule, thus, the primary interaction of 2.94 μm is the water molecule. For fluence values above the tissue ablation threshold, the absorption of laser radiation by the water provides to the molecule sufficient kinetic energy to produce a high pressure within tissue. As a consequence micro-explosions in sub-superficial irradiated tissue takes place. These micro-explosions cause a partial tissue rupture and a cavity is formed. Irradiating the tissue with fluences below the ablation threshold does not provide enough kinetic energy to the water molecules to cause the mentioned micro-explosions. The absorbed energy for the water molecules below ablation threshold results mainly in heat increasing the tissue temperature.

The CO_2 - 9.6 μm laser wavelength, on the other hand, is resonant with the vibration energy of the phosphate radical, resulting in a primary absorption of laser radiation in the mineral matrix. The phosphate radical concentration for the enamel is near 54.6 wt% [14].

The melt pattern after CO_2 laser irradiation observed in the dentin and enamel originated from the temperature rise above the hydroxyapatite melting point [15] and consequent cooling to the ambient temperature. The melted

© 2005 by Astro Ltd.
Published exclusively by WILEY-VCH Verlag GmbH & Co. KGaA

tissue has physical and chemical properties that differ from the natural tissue properties; consequently carious lesion progression is inhibited after CO_2 laser irradiation [16].

The maximum temperature rise for Er:YAG and CO_2 laser are responsible for the two different observed morphological pattern. During the CO_2 laser irradiation with 6 J/cm^2 the temperature rise at the surface is $\sim$1000 °C which is close to the hydroxyapatite melting point; on the other hand the surface temperature rise during Er:YAG irradiation with 7 J/cm^2 is $\sim$300 °C [11]. The surrounding region of the irradiated tissue is thermally altered by temperatures that depends on the irradiation parameters and tissue properties. The maximum temperature rise reached in a specific sub-surface layer is also higher during the CO_2 laser irradiation than during the Er:YAG laser irradiation.

The higher temperatures that the tissue are submitted in the surface and sub-surface layer also change the physical and chemical composition, as the water content, collagen or other protein content, crystallographic structure, carbonate or other radical present in the mineral matrix. These changes influence the tissue properties such as increase of the enamel acid resistance [16] by the carbonated lost or decrease the bond strength between the tissue and composite resin by the organic matrix denaturation [17].

The rough pattern with exposition of the prismatic structure and dentinal tubules observed in the Er:YAG laser irradiated enamel and dentin is originated from the water micro-explosion while the melting observed in CO_2 - 9.6 μm laser irradiated enamel and dentin is originated from the temperature rise above the hydroxyapatite melting point.

References

[1] L. Bachmann, R. Diebolder, R. Hibst, and D.M. Zezell, Appl. Spectrosc. Rev. **38**, 1 (2003).
[2] D.M. Zezell, S.C. Cecchini, C.P. Eduardo, et al., J. Clin. Laser Med. Surg. **13**, 283, (1995).
[3] R. Hibst and U. Keller, Lasers Surg. Med. **9**, 338 (1989).
[4] R. Hibst and U. Keller, Lasers Surg. Med. **9**, 345 (1989).
[5] R. Müllejans, G. Eyrich, W.H.M. Raab, and M. Frentzen, Lasers Surg. Med. **30**, 331 (2002).
[6] R.Z. LeGeros, G. Bonel, and R. Legros, Calcif. Tiss. Res. **26**, 111 (1978).
[7] V.Y. Zaichick and N.N. Ovchjarenko, J. Trace Microprobe Tech. **14**, 143 (1996).
[8] D. Fried, M.J. Zuerlein, C.Q. Le, and J.D.B. Featherstone, Lasers Surg. Med. **31**, 275 (2002).
[9] J.D.B. Featherstone and D. Fried, Med. Laser Appl. **16**, 181, (2001).
[10] M.J. Zuerlein, D. Fried, J.D.B. Featherstone, and W. Seka, IEEE J. Sel. Top. Quant. **5**, 1083 (1999).
[11] D. Fried, M. Zuerlein, J.D.B. Featherstone, et al., Appl. Surf. Sci. **127**, 852 (1998).
[12] R. Hibst and U. Keller, J. Dent. Res. **74**, 586 (1995).
[13] H.A. Wigdor and J.T. Walsh, Lasers Surg. Med. **30**, 261 (2002).
[14] M.F. Little and F.S. Casciani, J. Phys. Chem. **75**, 3167 (1966).
[15] J.T. Corcia and W.E. Moody, J. Dent. Res. **53**, 571 (1974).
[16] J.D.B. Featherstone, N.A. Barrett-Vespone, D. Fried, et al., J. Dent. Res. **77**, 1397 (1998).
[17] T.M. Marraccini, L. Bachmann, H.A. Wigdor, et al., Dent. Mat. (2005) (submitted).

© 2005 by Astro Ltd.
Published exclusively by WILEY-VCH Verlag GmbH & Co. KGaA