Published in final edited form as:

Proc SPIE Int Soc Opt Eng. 2015 February 24; 9306: . doi:10.1117/12.2083653.

Selective removal of dental caries with a diode-pumped Er:YAG laser

Ruth Yan, Kenneth H. Chan, Henry Tom, Jacob C. Simon, Cynthia L. Darling, and Daniel Fried*

University of California, San Francisco, San Francisco, CA 94143-0758

Abstract

Selective removal of caries lesions with high precision is best accomplished using lasers operating at high pulse repetition rates utilizing small spot sizes. Conventional flash-lamp pumped Er:YAG lasers are poorly suited for this purpose, but new diode-pumped Er:YAG lasers have become available operating at high pulse repetition rates. The purpose of this study was to measure the ablation rate and selectivity of sound and demineralized enamel and dentin for a 30 W diode-pumped Er:YAG laser operating with a pulse duration of 20-30- μ s and evaluate its potential for the selective removal of natural occlusal lesions on extracted teeth. Microradiography was used to determine the mineral content of the demineralized enamel and dentin of 300- μ m thick sections with natural caries lesions prior to laser ablation. The ablation rate was calculated for varying mineral content. In addition, near-IR reflectance measurements at 1500-1700-nm were used to guide the laser for the selective ablation of natural occlusal caries lesions on extracted teeth.

Keywords

Er:YAG laser; dental caries; near-IR imaging; selective laser ablation

1. Introduction

Image-guided laser ablation of dental caries requires the rapid acquisition of high-contrast images of areas of enamel and dentin demineralization that can be input into the laser-scanning system to selectively remove areas of demineralization. Computer control is now feasible due to the recent advances in compact high-speed laser scanning technology such as MEMS (Micro-Electro-Mechanical Systems) mirrors and miniature galvanometer “galvo” based scanners. One approach is to remove the lesion layer by layer, i.e. image the lesion then scan the laser and remove an outer layer of the lesion, then re-image and scan again repeating that process until the lesion is completely removed.

Previous approaches for guiding laser ablation have included fluorescence [1-3] and near-IR transillumination [4]. Near-IR reflectance imaging is ideally suited for acquiring high-contrast images for image guided ablation due to the weak light scattering from sound

enamel and the lack of interference from stains [5-7]. Stains which greatly interfere with visible light based methods do not interfere at near-IR wavelengths beyond 1300-nm, this is why visible reflectance measurements and fluorescence are of limited effectiveness in tooth occlusal surfaces [8, 9]

In our previous study presented last year we showed that near-IR reflectance in the wavelength regions coincident with increased water absorption namely 1450-nm and wavelengths higher than 1500-nm were ideally suited for this approach [14]. An important concern, essential for image-guided ablation, was that thermal modification of sound and demineralized tooth surfaces by the laser, could increase reflectivity from irradiated areas adversely influencing the lesion contrast and performance. We measured the lesion contrast at 1450-nm and from 1500-1700-nm before and after laser ablation had been initiated and those changes were acceptable [14].

For selective removal, low energy pulses and small spot sizes must be used to minimize the amount of tissue removed per laser pulse, therefore the laser has to be operated at high pulse repetition rates for practical removal rates. Until recently the only lasers that met this criteria were CO₂ lasers operating at the highly absorbed 9.3 and 9.6- μ m wavelengths and we have demonstrated that enamel and dentin can be most efficiently ablated using laser pulses of 10-15- μ s duration [15-17]. The flash-lamp pumped erbium solid-state lasers presently being used for dental hard tissue ablation are not suitable for this approach since they utilize high energy pulses and relatively low pulse repetition rates. Diode pumped solid-state (DPSS) Er:YAG lasers are now available operating with pulse repetition rates as high as 1-2 kHz and initial studies have been carried out demonstrating their utility for the ablation of dental hard tissues and bone [18-20].

The purpose of this study was to explore the potential of the diode pumped Er:YAG laser for the image guided ablation of caries lesions.

2. Materials and Methods

2.1 Sample Preparation

Twenty-one human teeth with suspected lesions in the occlusal surfaces were collected (CHR approved) and sterilized with gamma radiation. Five of the teeth were mounted in black orthodontic acrylic blocks. For the other sixteen teeth, a 300- μ m thick section was cut through the area of the lesion using a diamond saw, Isomet 5000, Buehler (Lake Bluff, IL). Samples were stored in a moist environment of 0.1% thymol to maintain tissue hydration and prevent bacterial growth. The samples were divided into three groups as shown in Fig. 1. Group 1 was used to determine the respective ablation rates of sound and demineralized enamel and dentin using Depth Composition Digital Microscopy (DCDM), Polarized Light Microscopy (PLM) and Transverse Microradiography (TMR). Group 2 was used for the image-guided ablation of lesions with varying mineral content using near-IR reflectance after analysis with DCDM, PLM and TMR. Group 3 was used to investigate near-IR image guided ablation of natural lesions in the occlusal surfaces of whole teeth and DCDM, PLM and Optical Coherence Tomography (OCT) were used for analysis before and after ablation. The outlines of 2.5 $\times$ 2.5 mm windows approximately 50- μ m deep were cut in lesion areas for

the samples of groups 2 & 3 using the Er:YAG laser around the suspected lesion area. The channels cut by the laser serve as reference points for serial sectioning and are sufficiently narrow that they do not interfere with calculations of the image contrast.

2.2 Laser Irradiation

Samples were irradiated using a DPSS Er:YAG laser, Model DPM-30 (Pantec Engineering, Liechtenstein) operated with pulse durations varying from 20-100- μ s and pulse repetition rates of up to 500-Hz. The laser energy output was monitored using a power meter EPM 1000, Coherent-Moletron (Santa Clara, CA), and the Joulemeter ED-200 from Gentec (Quebec, Canada). A high-speed XY-scanning system, Model ESP 301 controller with ILS100PP and VP-25AA stages (Newport, Irvine, CA) was used to scan the samples across the laser beam. Designated sound and lesion areas (boxes) on each tooth were irradiated by the laser. The laser was focused to a spot size of $\sim 150\text{-}\mu\text{m}$ using two ZnSe lenses. A repetition rate of 500-Hz was used with point to point scanning with each spot separated by 50- μm . A pressure air-actuated fluid spray delivery system consisting of a 780S spray valve, a Valvemate 7040 controller, and a fluid reservoir from EFD, Inc. (East Providence, RI) was used to provide a uniform spray of fine water mist onto the tooth surfaces at 2 mL/min.

2.3 Near-IR Cross Polarization Reflectance Images (NIR)

In order to acquire reflected light images, linearly polarized and collimated light from a 150-W fiber-optic illuminator, Model FOI-150 from the E Licht Company (Denver, Colorado) was used to illuminate the samples at an incident angle of 30° . Polarizers were placed after the light source and before the detector to remove specular reflection (glare) that interferes with measurements of the lesion contrast. The NIR reflectance images were captured using a 320×240 element InGaAs area camera SU320-KTSX from Sensors Unlimited (Princeton, NJ) sensitive from 900-1700-nm with a 25- μm pixel pitch. The camera was equipped with a Model SWIR-35 lens from Navitar, Inc. (Rochester, NY). Reflectance measurements were taken for three spectral bands using two bandpass filters and a longpass filter. The band pass filters were BP1300-90 and BP1460-85 from Spectrogon (Parsippany, NJ) and the 1500-nm long-pass filter was the FEL 1500 from Thorlabs (Newton, NJ).

2.4 Digital Microscopy (DCDM)

Tooth surfaces were examined after laser irradiation using an optical microscopy/3D surface profilometry system, the VHX-1000 from Keyence (Elmwood, NJ). Two lenses were used, the VH-Z25 with a magnification from 25 to 175 $\times$ and the VH-Z100R with a magnification of 100-1000 $\times$. Depth composition digital microscopy images (DCDM) were acquired by scanning the image plane of the microscope and reconstructing a depth composition image with all points at optimum focus displayed in a 2D image. The Keyence 3-D shape measurement software, VHX-H3M, was used to correct the tilt of the sample and measure the variation in depth over the enamel in the ablated areas.

2.5 PS-OCT System (OCT)

An all-fiber-based optical coherence domain reflectometry (OCDR) system with polarization maintaining (PM) optical fiber, high-speed piezoelectric fiber-stretchers and

two balanced InGaAs receivers that was designed and fabricated by Optiphase, Inc., Van Nuys, CA was used. This two-channel system was integrated with a broadband superluminescent diode (SLD) Denselight (Jessup, MD) and a high-speed XY-scanning system (ESP 300 controller and 850G-HS stages, National Instruments, Austin, TX) for *in vitro* optical coherence tomography. The spectral output of the 15-mW SLD was centered at 1317 nm with a spectral bandwidth full-width at half-maximum (FWHM) of 84 nm. This configuration provided a lateral resolution of approximately 20 μm and an axial resolution of 10 μm in air. The system is described in greater detail in reference [21]. The PS-OCT scans were used to confirm the presence of the occlusal lesions.

2.6 Polarized Light Microscopy (PLM)

After sample imaging was completed, approximately 200 μm thick serial sections were cut using an Isomet 5000 saw (Buehler, IL), for polarized light microscopy (PLM). PLM was carried out using a Meiji Techno RZT microscope (Meiji Techno Co., LTD, Saitama, Japan) with an integrated digital camera, Canon EOS Digital Rebel XT (Canon Inc., Tokyo, Japan). The sample sections were imbibed in water and examined in the brightfield mode with crossed polarizers and a red I plate with 500-nm retardation.

2.7 Digital Transverse Microradiography (TMR)

A custom-built digital TMR system was used to measure mineral loss in the different partitions of the sample. A high-speed motion control system with Newport (Irvine, CA) UTM150 and 850G stages and an ESP300 controller coupled to a video microscopy and laser targeting system was used for precise positioning of the tooth samples in the field of view of the imaging system. The volume percent mineral for each sample thin section was determined by comparison with a calibration curve of X-ray intensity vs. sample thickness created using sound enamel sections of 86.3 ± 1.9 vol.% mineral varying from 50 to 300 μm in thickness using Igor Pro image analysis software. The calibration curve was validated via comparison with cross-sectional microhardness measurements, $r^2 = 0.99$ [22].

2.8 Image Analysis

Line profiles were extracted at the same position from the most severe area of each image across each 2.5×2.5 mm window and lesion or image contrast was calculated using the equation $(I_L - I_S)/I_L$; where I_S is the mean intensity of the sound enamel outside the window area, and I_L is the mean intensity of the lesion inside the window for reflectance measurements. The left (sound) box and the central (lesion) box were used for both the pre- and post contrast calculations. Both the left (sound) box and the central (lesion) box were irradiated by the laser (post contrast) The QLF measurements have the reverse contrast, i.e., the intensity in sound areas is higher than for the lesion areas.

All image analysis was carried out using Igor pro software (Wavemetrics, Lake Oswego, OR). A repeated measures one-way analysis of variance (ANOVA) followed by the Tukey-Kramer post-hoc multiple comparison test was used to compare groups employing Prism software (GraphPad, San Diego, CA).

3. Results and Discussion

3.1 Group 1 - Tooth Sections

Initial Er:YAG ablation rates were assessed using Group 1 samples. PLM and TMR were used to confirm lesion presence. Incisions were produced on the Group 1 sections ($n = 8$) by repeated Er:YAG laser scans (12 passes) as shown in Fig. 2. The ablation depths were analyzed using DCDM. The results shown in Fig. 6 suggest that the Er:YAG selectively ablated demineralized enamel more effectively than it did sound enamel ($p < 0.05$).

In addition, in reference to the DCDM images on the right side of Fig. 2, the ablated sound enamel appears rough and has higher reflectivity and some small peripheral microfractures. However, dentin and demineralized enamel appeared to be ablated successfully with no sign of thermal or mechanical damage.

3.2 Group 2 - Tooth Sections

As shown in Fig. 3, PLM and TMR were again used to confirm lesion presence. The Er:YAG was used to create the outline of a 2.5×2.5 mm box to define a region of interest (ROI). For each sample, near-IR reflectance images of the ROI were obtained and then used to guide the Er:YAG to selectively ablate demineralized tooth structure. The before and after ablation DCDM images in Fig. 3 show that an area of demineralized enamel seen in the corresponding PLM and TMR images was successfully targeted and ablated.

3.3 Group 3 - Whole Teeth

Near-IR reflectance images were used to guide the Er:YAG laser to selectively removed demineralized enamel from the 2.5×2.5 mm ROI on tooth occlusal surfaces. Near-IR reflectance images were taken after every 10-20 iterations (laser scans). Figure 4 shows NIR and DCDM images during treatment of one tooth at four different time points. Ablation was stopped after 200 scans. Figure 5 shows the PS-OCT images taken before and after removal. The image acquired before removal shows a lesion, indicated by the increased signal intensity with depth. The image after removal shows successful ablation of the corresponding lesion area. The PLM post-ablation image of the sectioned sample likewise reveals removal of almost the entire lesion area.

3.4 Summary

Ablation of dental hard tissues was achieved using the Er:YAG laser operating at high pulse repetition rates with minimal peripheral thermal damage. In addition, since water is the primary absorber of Er:YAG radiation and demineralized areas are more porous and have a higher water content the ablation rate is significantly higher for demineralized vs sound tissues.

While ablating the Group 3 whole teeth occlusal samples, after 200 scans both the PS-OCT and PLM images show that the Er:YAG laser had not yet reached dentin (Fig. 5). It is likely dynamic focusing will be needed due to the small depth of focus. Another problem is that the ablated sound enamel areas manifested a very rough appearance with high reflectivity. The reflectivity was of a similar magnitude to demineralization and could not be

differentiated. This phenomenon created complications during ablation of the Group 3 whole teeth samples. Further studies are being carried utilizing a range of incident fluence, pulse duration and rate of water spray to establish the irradiation conditions that minimize the surface changes on enamel.

In conclusion, these studies indicate that the diode-pumped solid state Er:YAG laser with its high pulse repetition rate and selectivity for demineralized enamel, holds great potential for the image-guided selective removal of dental caries.

Acknowledgments

This work was supported by NIH/NIDCR Grants R01-DE14698 and R01-DE19631.

References

1. Eberhard J, Bode K, Hedderich J, Jepsen S. Cavity size difference after caries removal by a fluorescence-controlled Er:YAG laser and by conventional bur treatment. *Clin Oral Investigations*. 2008; 12(4):311–8.
2. Eberhard J, Eisenbeiss AK, Braun A, Hedderich J, Jepsen S. Evaluation of selective caries removal by a fluorescence feedback-controlled Er:YAG laser in vitro. *Caries Res*. 2005; 39(6):496–504. [PubMed: 16251795]
3. Jepsen S, Acil Y, Peschel T, Kargas K, Eberhard J. Biochemical and morphological analysis of dentin following selective caries removal with a fluorescence-controlled Er:YAG laser. *Lasers Surg Med*. 2008; 40(5):350–7. [PubMed: 18563782]
4. Tao YC, Fried D. Near-infrared image-guided laser ablation of dental decay. *J Biomed Optics*. 2009; 14(5):054045.
5. Bühler CM, Ngaotheppitak P, Fried D. Imaging of occlusal dental caries (decay) with near-IR light at 1310-nm. *Opt Express*. 2005; 13(2):573–582. [PubMed: 19488387]
6. Jones G, Jones RS, Fried D. Transillumination of interproximal caries lesions with 830-nm light. *Lasers in Dentistry X Proc of SPIE*. 2004; 5313:17–22.
7. Jones RS, Huynh GD, Jones GC, Fried D. Near-IR Transillumination at 1310-nm for the Imaging of Early Dental Caries. *Opt Express*. 2003; 11(18):2259–2265. [PubMed: 19466117]
8. Borsboom PCF, ten Bosch JJ. Fiber-optic scattering monitor for use with bulk opaque material. *Appl Optics*. 1982; 21(19):3531–3535.
9. ten Bosch JJ, van der Mei HC, Borsboom PCF. Optical monitor of in vitro caries. *Caries Res*. 1984; 18:540–547. [PubMed: 6593126]
10. Wu J, Fried D. High contrast near-infrared polarized reflectance images of demineralization on tooth buccal and occlusal surfaces at $\lambda = 1310$ -nm. *Lasers Surg Med*. 2009; 41(3):208–13. [PubMed: 19291753]
11. Chung S, Fried D, Staninec M, Darling CL. Multispectral near-IR reflectance and transillumination imaging of teeth. *Biomed Opt Express*. 2011; 2(10):2804–2814. [PubMed: 22025986]
12. Fried WA, Darling CL, Chan K, Fried D. High Contrast Reflectance Imaging of Simulated Lesions on Tooth Occlusal Surfaces at Near-IR Wavelengths. *Lasers Surg Med*. 2013; 45:533–541. [PubMed: 23857066]
13. Simon JC, Chan KH, Darling CL, Fried D. Multispectral near-IR reflectance imaging of simulated early occlusal lesions: Variation of lesion contrast with lesion depth and severity. *Lasers in Surg Med*. 2014; 46(3):203–215. [PubMed: 24375543]
14. LaMantia NR, Tom H, Chan KH, Simon JC, Darling CL, Fried D. High contrast optical imaging methods for image guided laser ablation of dental caries lesions. *Lasers in Dentistry XX Proc Of SPIE*. 2014; 89290:1–7.

15. Zuerlein M, Fried D, Featherstone J, Seka W. Optical properties of dental enamel at 9 - 11 μm derived from time-resolved radiometry. *Special Topics IEEE J Quant Elect*. 1999; 5(4):1083–1089.
16. Zuerlein M, Fried D, Featherstone JDB. Modeling the Modification Depth of carbon Dioxide Laser Treated Enamel. *Lasers Surg Med*. 1999; 25:335–347. [PubMed: 10534750]
17. Fried D, Murray MW, Featherstone JDB, Akrivou M, Dickenson KM, Duhn C. Dental hard tissue modification and removal using sealed TEA lasers operating at $\lambda=9.6\ \mu\text{m}$. *J Biomedical Opt*. 2001; 6(2):231–238.
18. Stock K, Diebold R, Hausladen F, Hibst R. Efficient bone cutting with the novel diode pumped Er:YAG laser system: in vitro investigation and optimization of the treatment parameters. *Photonic Therapeutics and Diagnostics X, Proc of SPIE*. 2014; 8926:1–6.
19. Stock K, Diebold R, Hausladen F, Wurm H, Lorenz S, Hibst R. Primary investigations on the potential of a novel diode pumped Er:YAG laser system for bone surgery. *Photonic Therapeutics and Diagnostics IX Proc of SPIE*. 2013; 8565, D:1–8.
20. Stock K, Hausladen F, Hibst R. Investigations on the potential of a novel diode pumped Er:YAG laser system for dental applications. *Lasers in Dentistry XVIII, Proc of SPIE*. 2012; 8208, D:1–5.
21. Fried D, Xie J, Shafi S, Featherstone JDB, Breunig T, Lee CQ. Early detection of dental caries and lesion progression with polarization sensitive optical coherence tomography. *J Biomed Optics*. 2002; 7(4):618–627.
22. Darling CL, Featherstone JDB, Le CQ, Fried D. An automated digital microradiography system for assessing tooth demineralization. *Lasers in Dentistry VX Proc of SPIE*. 2009; 7162:1–7.

Fig. 1.

Three groups of samples used in the study along with the methods employed.

Fig. 2.

Laser incisions on a 300- μ m thick section (Group 1). PLM (20 $\times$ magnification) and TMR images are shown of the lesion area before laser ablation. DCDM (visible) images are shown of the lesion area at 100 $\times$ magnification after making three incisions across the sample (6 scans or iterations). Higher magnification (300 $\times$) DCDM images are shown of the incision areas indicated by the red boxes for sound and demineralized enamel and dentin.

Fig. 3. PLM (10 $\times$ magnification), TMR and NIR images are shown of the lesion area before laser ablation of a 300-mm thick section (Group 2). The green outline in the 5 $\times$ 5 mm ROI in the near-IR image shows the areas selected for ablation. DCDM (visible) images are shown at 100 $\times$ magnification before and after the lesion area was ablated by the laser (4 scans or iterations).

Fig. 4. DCDM and NIR images of one of the samples (Group 3) with an occlusal lesion at different time points during laser removal: (A) before, and after (B) 52, (C) 120, (D) 200 scans. The designated lesion areas for ablation are indicated by the green outlines in the NIR images.

Fig. 5. OCT b-scans before and after removal of one of the occlusal lesions in a section of Group 3. A PLM image at 20 $\times$ magnification is shown after removal of the lesion. Note the small protrusion of reduced reflectivity which was not removed.

Fig. 6.
Mean $\pm$ s.d ablation depths using digital microscopy.