Photoacoustic imaging of teeth for dentine imaging and enamel characterization

Periyasamy, Vijitha; Rangaraj, Mani; Pramanik, Manojit

2018

Periyasamy, V., Rangaraj, M., & Pramanik, M. (2018). Photoacoustic imaging of teeth for dentine imaging and enamel characterization. Proceedings of SPIE - Lasers in Dentistry XXIV, 10473, 1047309-.

<https://hdl.handle.net/10356/87349>

<https://doi.org/10.1117/12.2286733>

© 2018 Society of Photo-Optical Instrumentation Engineers (SPIE). This paper was published in Proceedings of SPIE - Lasers in Dentistry XXIV and is made available as an electronic reprint (preprint) with permission of SPIE. The published version is available at: [<http://dx.doi.org/10.1117/12.2286733>]. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper is prohibited and is subject to penalties under law.

Downloaded on 26 Apr 2023 07:14:21 SGT

Photoacoustic imaging of teeth for dentine imaging and enamel characterization

Vijitha Periyasamy^a, Mani Rangaraj^b, and Manojit Pramanik^{a*}

^a School of Chemical and Biomedical Engineering, Nanyang Technological University, 62 Nanyang Drive, Singapore 637459;

^b Department of Periodontology, Faculty of Dental Sciences, M. S. Ramiah University of Applied Sciences, Bangalore-560054, Karnataka, India.

ABSTRACT

Early detection of dental caries, cracks and lesions is needed to prevent complicated root canal treatment and tooth extraction procedures. Resolution of clinically used x-ray imaging is low, hence optical imaging techniques such as optical coherence tomography, fluorescence imaging, and Raman imaging are widely experimented for imaging dental structures. Photoacoustic effect is used in photon induced photoacoustic streaming technique to debride the root canal. In this study, the extracted teeth were imaged using photoacoustic tomography system at 1064 nm. The degradation of enamel and dentine is an indicator of onset of dental caries. Photoacoustic microscopy (PAM) was used to study the tooth enamel. Images were acquired using acoustic resolution PAM system. This was done to identify microscopic cracks and dental lesion at different anatomical sites (crown and cementum). The PAM tooth profile is an indicator of calcium distribution which is essential for demineralization studies.

Keywords: Photoacoustics tomography, photoacoustic microscopy, teeth imaging, dentine, demineralization.

1. INTRODUCTION

Teeth undergo constant demineralization and remineralization [1]. When demineralization is faster than remineralization cracks or lesions start developing on teeth. The pH of oral cavity is naturally at 5.5. When the pH alters due to bad oral hygiene, bacteria start decaying on tooth. Tooth consists of enamel and dentine. In most of the cases caries or lesions develop on enamel. These surficial lesions or caries have to be treated before it penetrates deeper to the dentine. Dentine is the bed of nerves and blood vessels which when affected lead to extraction of the tooth. Dental caries and white lesions are treatable if they are detected at the early stages. But the deformity is treatable only if it is less than 100 μm . The bit wing x-ray imaging is the clinically used dental diagnostic tool. One of the disadvantages of x-ray imaging is the signal deteriorated at the occluded surfaces. Exposure to x-ray radiation pre- and post-childbirth is unsafe for the mother. The image resolution has to be improved early detection of the dental deformities [2].

Optical coherence tomography (OCT) is widely used in dentistry due to resolution of 20 μm [3]. The blood vessels and other microstructures of oral cavity are quantitatively and qualitatively imaged using OCT due its high spatial resolution [4, 5]. Efficiency of OCT to image dental caries, periodontal diseases and oral cancer are well established. The resolution of OCT is high the depth of penetration is as less as 2.5 mm in hard tissue such as enamel and dentine. Even though there are research outcomes on fluorescence and Raman spectroscopy for dental diagnosis, the reduced penetration depth and increased scanning time are the disadvantages of these modalities [6].

Ultrasound (US) imaging is another imaging modality which is widely used in dental diagnosis [7]. US is used in the fields of dental scanning, caries detection, dental fractures, soft tissue and peripheral lesions, maxillofacial fractures, periodontal bony defects, gingival and muscle thickness, temporomandibular disorders and implant dentistry [8]. Even though there are hand-held B-mode probes for dental scanning which works on the acoustic differences between the

* manojit@ntu.edu.sg;

enamel and dentine, these probes have not been tested on large populations and further improvements are required to be used in clinical environment. US images of caries were compared with bite-wing radiographs and the conclusion was both have similar levels of accuracy.

Photoacoustic (PA) tomography is another imaging which utilizes the optical contrast and the penetration depth of ultrasound imaging [9-11]. The dental caries are detected using PA images or signals [12-16]. B-mode and S-mode PA images of the extracted tooth were studied [17]. The B-mode images represented the intensity of PA which corresponds to the macrostructures of the teeth. S-mode images are the slope of each pixel and these images represented the microstructures of teeth. PA microscopy was also used to image the dental structures [18]. The caries and white spot lesions on the tooth were detected with higher resolution. PA signal at 532 nm and 1064 nm was studied. The frequency components in the PA signals at these two wavelengths were seen to correlate to the hematocrit percentage in the dental pulp [19]. This property which is similar to dental pulse oximeter represents the health (or decay) condition of the dental pulp. Feasibility of PA imaging for dental implants and periodontal disorders has also been studied. In this paper we image the extracted teeth in photoacoustic (PA) tomography and microscopy system. The feasibility of PAT and PAM for dental imaging has been studied. PA signal strength varies in normal teeth, caries and in metal filling.

Figure 1. Illumination plane and acoustic plane representation for photoacoustic tomography and microscopy system. (a) Illumination (green cone) in sagittal plane and acoustic (gray ring) collection is in transverse plane. (b) Illumination (green doughnut) and acoustic collection (grey cylinder) is in sagittal plane. The arrows indicate the direction of acoustic collection

2. METHODS AND MATERIALS

Two PA imaging systems were used to image the human extracted teeth in sagittal and/or transverse plane [20, 21]. In PAT system, laser beam of 1064 nm at 10 Hz with a beam diameter of 5 mm from Q-switched Nd:YAG laser was illuminated on the tooth sample [20, 22, 23]. The generated PA signal was acquired using a 2.25 MHz central frequency ultrasound transducer (UST) from Olympus, Nondestructive ultrasound testing, V306-SU. Active area of the transducer was 13 mm. The transducer was mounted on a custom made circular plate which was rotated using rotatory motor. Figure 1(a) depicts the positioning of a sample tooth for PAT system. Illumination is along the sagittal plane and signal is acquired along the transverse plane. The signal from UST was digitized and transferred to a desktop using data acquisition card (DAQ) (compuscope 4227, GaGE) which was operated at 25 Ms/s. LabView interface was used for data collection and MATLAB programs were written to reconstruct the PA intensity images from A-lines using simple delay-and-sum algorithm [24].

Acoustic resolution photoacoustic microscopy system consists of diode-pumped solid-state Nd:YAG laser operated at 1064 nm [21, 25, 26]. Pulse repetition rate was 5000 Hz and the sample was illuminated by a doughnut shaped beam of 2 mm. PA signal was collected using 30 MHz UST (Fig 1b). Illumination and PA signal collection is along the sagittal plane. The scanning assembly was mounted on tri-axial stage (PLS 85 and VT 80 from Physik Instrumente). UST signal was amplified using ZFL-500LN, Mini Circuits amplifier and data was acquired using DAQ card M4i, 4420, Spectrum. The scanning was done using LabVIEW and the image processing was done in MATLAB. Less than 1W of laser beam was focused on photodiode to synchronize the data acquisition process with each laser pulse. PA signal along the depth of the sample was acquired by raster scanning x and y -axis. Maximum amplitude projection (MAP) images and depth profile image is discussed here.

Teeth for four subjects extracted due to decay or caries was used in this study. Patients consent was also obtained for the use of these samples for research. Extracted teeth were washed thoroughly and stored in saline. Three molar teeth and one premolar tooth were chosen for this study. One molar had caries (T1) and premolar (T2) and another molar (T3) had lesion. One of the molar (T4) had a metal filling and lesion. The samples were fixed in 10% agar base and immersed in a water tank during imaging. The samples were mostly fixed in upright position and imaged in sagittal axis. T1, T2 and T4 were scanned in PAT system, and T2, T3 and T4 was scanned in PAM system. To study the feasibility of PA in periodontics, T2 was fixed horizontally to enable imaging along transverse plane. Teeth were replaced to saline solution after the imaging procedure.

Figure 2. Camera captured images and photoacoustic tomography image of tooth T1 (a, b), T2 (c, d) and T3 (e, f).

3. RESULTS AND DISCUSSION

Optical fluence on the sample during PAT and PAM imaging was maintained with American National Standard for Safe Use of Lasers [27]. 600 A-lines were acquired over 60 seconds in PAT system. A-lines were reconstructed into an image of 500 grids of size 200 μm in x- and y- axis. The macro- and micro- sized caries of T1 are detected in the PAT image. The structural information identified in visual examination of the tooth [Fig. 2(a)] was also highlighted in PA image [Fig. 2(b)]. The caries which have different mineral distribution gives higher PA signal compared to the normal tooth. Studies are yet to be done to correlate the PA signal intensity to the mineral content of the tooth. The lesion seen visually in T2 [Fig. 2 (c)] had high intensity in PA image [Fig. 2(d)]. Lesion/stain gives higher PA signal due to the chromophores present. As discussed earlier, the correlation between the PA intensity and the chromophore content in the dental structure is not explored. Figure 3(e) is the camera captured image of T4 which has metal and lesion. It is well known that, metal gives a strong PA signal. Hence, this tooth was chosen to study the feasibility of PA imaging of metal filled tooth. As expected, the signal from metal filling dominated the signal due to lesion. Further experimental designs are needed to image such special samples.

Photoacoustic tomography images did have information of tooth deformities, but the resolution of PAT is in orders of few hundreds of microns, hence photoacoustic microscopy images were acquired. Tooth T2 [Fig. 3(a)] which had a lesion on the surface was imaged in transverse plane. The lesion does give a high signal. Other bright spots are also seen in the PAM image [Fig. 3(b)]. Additional information to be noted is the bright signal at the tip of the tooth, (pointed by

an arrow). The brightness can be attributed to the difference in the mineral deposition. Since the resolution of the acoustic PAM is a few tens of microns, customizing PAM for clinical set-up will help in early detection of the white spot lesions, caries and decay. Figure 3(d) is camera image of tooth T3 and Fig. 3(e) is the depth profile of the tooth. Depth profile is the location within or on the surface of the tooth where the PA intensity is highest. The lesion on the tooth in the shape of “+” is deeper as per PA image and visual examination. The smaller lesion in the left-bottom quadrant is also seen in the PA image.

Figure 3. Camera images and photoacoustic microscopy images of teeth. (a) Tooth T2, (b) MAP of T2, (c) Tooth T3, and (d) depth profile of MAP of T3.

Sample T4 [Fig. 4(a)] with metal filling was imaged using PAM. MAP image represents the metal boundaries. Two independent metal fillings are identifiable in the PAM images. T4 is inset in the figure for comparison. Figure 4(b) is the metal filling seen as in 3D along the sagittal plane. Even though PA signal from metal dominates any other signal from tooth, PAM images of these filling would help in characterizing the different filling materials. The efficiency of filling at the surface is easy to examine for the dentist but the deeper filling needs imaging techniques.

4. CONCLUSION

Photoacoustic imaging of human teeth using tomography and microscopy has been discussed in this paper. PAT and PAM images of tooth do represent caries and lesions. PAT system can only image extracted tooth. The acoustic resolution PAM system discussed here is not clinical, but there are handheld PAM system currently used in dermatological application which can be further modified for teeth imaging through cheek muscle. Handheld clinical photoacoustic imaging systems widely used for sentinel lymph node imaging and breast tumor imaging can be modified for dental tooth imaging [28-30]. Photoacoustic imaging for dental application is essential in clinic to assist dentist. Applications of PA in analysis the dental pulp, hematocrit percentage, and jaw implants will be the future work.

Figure 4. (a) 2D and (b) 3D image of metal filling of tooth T4.

ACKNOWLEDGEMENT

Authors would like to thank Dr Mohesh Moothanchery for the guidance on steps involved in using the acoustic resolution photoacoustic microscopy system. The research is supported by Tier 2 grant funded by the Ministry of Education in Singapore (ARC2/15: M4020238), and the Singapore Ministry of Health's National Medical Research Council (NMRC/OFIRG/0005/2016: M4062012). Authors have no relevant financial interests in the manuscript and no other potential conflicts of interest to disclose.

REFERENCES

- [1] C. L. Darling, G. D. Huynh, and D. Fried, "Light scattering properties of natural and artificially demineralized dental enamel at 1310nm," *Journal of biomedical optics*, 11(3), 034023-034023-11 (2006).
- [2] A. D. Association, "Dental radiographic examinations: recommendations for patient selection and limiting radiation exposure," Chicago: ADA, (2012).
- [3] Y.-S. Hsieh, Y.-C. Ho, S.-Y. Lee *et al.*, "Dental Optical Coherence Tomography," *Sensors*, 13(7), 8928 (2013).
- [4] B. W. Colston, M. J. Everett, L. B. Da Silva *et al.*, "Imaging of hard- and soft-tissue structure in the oral cavity by optical coherence tomography," *Applied Optics*, 37(16), 3582-3585 (1998).
- [5] L. O. Fernandes, C. C. B. O. Mota, L. S. A. Melo *et al.*, "In vivo assessment of periodontal structures and measurement of gingival sulcus with optical coherence tomography: a pilot study," *Journal of biophotonics*, 10(6-7), 862-869 (2017).
- [6] A. Akkus, D. Karasik, and R. Roperto, "Correlation between micro-hardness and mineral content in healthy human enamel," *Journal of clinical and experimental dentistry*, 9(4), e569 (2017).
- [7] J. Marotti, S. Heger, J. Tinschert *et al.*, "Recent advances of ultrasound imaging in dentistry—a review of the literature," *Oral surgery, oral medicine, oral pathology and oral radiology*, 115(6), 819-832 (2013).
- [8] Y. Zheng, E. Y. Maeva, A. Denisov *et al.*, [Ultrasound imaging of human teeth using a desktop scanning acoustic microscope] Springer, (2002).
- [9] P. K. Upputuri, and M. Pramanik, "Recent advances toward preclinical and clinical translation of photoacoustic tomography: a review," *Journal of Biomedical Optics*, 22(4), 041006 (2017).
- [10] L. V. Wang, [Photoacoustic imaging and spectroscopy] CRC press, (2009).

- [11] P. K. Upputuri, K. Sivasubramanian, C. S. K. Mark *et al.*, "Recent developments in vascular imaging techniques in tissue engineering and regenerative medicine," BioMed Research International, 2015, 9 (2015).
- [12] A. Yamada, S. Kakino, and Y. Matsuura, "Detection of Photoacoustic Signals from Blood in Dental Pulp," Optics and Photonics Journal, 6(09), 229 (2016).
- [13] Y. H. El-Sharkawy, Y. Badr, M. Gadallah *et al.*, "Diagnostic of human teeth using photoacoustic response.," Biomedical Optics, 613701-613701-9 (2006).
- [14] T. Koyama, S. Kakino, and Y. Matsuura, "Photoacoustic imaging of hidden dental caries by using a fiber-based probing system.," SPIE Technologies and Applications of Structured Light, 1025119-1025119-3 (2017).
- [15] C. Lin, F. Chen, A. Hariri *et al.*, "Photoacoustic Imaging for Noninvasive Periodontal Probing Depth Measurements," Journal of dental research, 0022034517729820 (2017).
- [16] T. Li, and R. Dewhurst, "Photoacoustic non-destructive evaluation and imaging of caries in dental samples.," AIP Conference Proceedings, 1211, 1574-1581 (2010).
- [17] R. Cheng, J. Shao, X. Gao *et al.*, "Noninvasive Assessment of Early Dental Lesion Using a Dual-Contrast Photoacoustic Tomography," Scientific Reports, 6, 21798 (2016).
- [18] B. Rao, X. Cai, C. Favazza *et al.*, "Photoacoustic microscopy of human teeth.," Proc. of SPIE, 7884, 78840U-1 (2011).
- [19] Y. H. El-Sharkawy, and A. F. El Sherif, "Photoacoustic diagnosis of human teeth using interferometric detection scheme," Optics & Laser Technology, 44(5), 1501-1506 (2012).
- [20] P. K. Upputuri, and M. Pramanik, "Performance characterization of low-cost, high-speed, portable pulsed laser diode photoacoustic tomography (PLD-PAT) system," Biomedical Optics Express, 6(10), 4118-29 (2015).
- [21] M. Moothanchery, and M. Pramanik, "Performance Characterization of a Switchable Acoustic and Optical Resolution Photoacoustic Microscopy System," Sensors, 17(2), 357 (2017).
- [22] P. K. Upputuri, V. Periyasamy, S. K. Kalva *et al.*, "A High-performance compact photoacoustic tomography system for in vivo small-animal brain imaging," Journal of Visualized Experiments(124), e55811 (2017).
- [23] P. K. Upputuri, and M. Pramanik, "Dynamic in vivo imaging of small animal brain using pulsed laser diode-based photoacoustic tomography system," Journal of Biomedical Optics, 22(9), 090501 (2017).
- [24] S. K. Kalva, and M. Pramanik, "Experimental validation of tangential resolution improvement in photoacoustic tomography using a modified delay-and-sum reconstruction algorithm," Journal of Biomedical Optics, 21(8), 086011 (2016).
- [25] M. Moothanchery, A. Sharma, and M. Pramanik, "Switchable Acoustic and Optical Resolution Photoacoustic Microscopy for in vivo small-animal blood vasculature imaging," Journal of Visualized Experiments(124), e55810 (2017).
- [26] M. Moothanchery, R. Z. Seeni, C. Xu *et al.*, "In vivo studies of transdermal nanoparticle delivery with microneedles using photoacoustic microscopy," Biomedical Optics Express, 8(12), 5483-5492 (2017).
- [27] "American National Standard for Safe Use of Lasers," ANSI Standard Z136.1-2007, NY, (2007).
- [28] K. Sivasubramanian, V. Periyasamy, and M. Pramanik, "Non-invasive sentinel lymph node mapping and needle guidance using clinical handheld photoacoustic imaging system in small animal," Journal of Biophotonics, (2018 (In Press)).
- [29] K. S. Valluru, and J. K. Willmann, "Clinical photoacoustic imaging of cancer," Ultrasonography, 35(4), 267 (2016).
- [30] K. Sivasubramanian, V. Periyasamy, and M. Pramanik, "Hand-held clinical photoacoustic imaging system for real-time non-invasive small animal imaging," Journal of Visualized Experiments, 128, e56649 (2017).