

***In vitro* imaging of remaining dentin and pulp chamber by optical coherence tomography: comparison between 850 and 1280 nm**

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Abstract. We report the application of optical coherence tomography (OCT) to generate images of the remaining dentin and pulp chamber of *in vitro* human teeth. Bidimensional images of remaining dentin and of the pulp chamber were obtained parallel to the long axis of the teeth, by two OCT systems operating around 1280 and 850 nm, and compared to tomography images using the i-CAT® Cone Beam Volumetric Tomography system as the gold standard. The results demonstrated the efficacy of the OCT technique; furthermore, the wavelength close to 1280 nm presented greater penetration depth in the dentine than 850 nm, as expected from scattering and absorption coefficients. The OCT technique has great potential to be used on clinical practice, preventing accidental exposure of the pulp and promoting preventive restoration treatment. © 2009 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.3103584]

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1 Introduction

The success of the dental treatment, particularly restoration, depends on the integral knowledge of the properties, structure, and function of the complex to dentin-pulp, which constitutes the necessary biological basis for making clinical decisions. Despite the differences in structure and composition, pulp and dentin are integrally connected in the sense that physiologic and pathologic reactions in one of the tissues will also affect the other. The two tissues have a common embryonic origin and also remain in an intimate relationship throughout the life of the vital tooth. Anything that affects dentin will affect the pulp and vice versa.¹

Many factors are involved in the pulpal response, such as cytotoxicity of the dental material, the application method of the restorative material, and the presence of bacteria. However, it seems that the effects of a restorative preparation, patient age, and remaining dentin thickness between cavity floor and pulp tissue play an important role in the intensity of pulpal response and stimulation of tertiary dentin deposition.²

In addition, during excavation procedures and cavity and crown preparation, the pulp may be accidentally exposed.

Knowledge of the configuration of the pulpal space and the pulp-dentin complex morphology plays an important role to prevent iatrogenic or so-called accidental exposure of the pulp. It is often difficult in clinical practice and with conventional image techniques, such as X-ray, to identify the exact dimensions of the internal tooth anatomy.³

To detect the depth of the dental cavity in relation to the pulpal chamber, the professionals withhold information collected through the clinical examination—visual and tactile inspection—and of the radiographic examination. These methods are subjective, which may lead to the wrong choice for the ideal treatment. Moreover, the radiographic procedure possesses some limitations for presenting overlapping of anatomical structures, for being a static method and emitting ionizing radiation.⁴

The optical coherence tomography (OCT) consists of a new imaging technique for diagnosis that produces bi- or three-dimensional pictures, with a few microns of spatial resolution, and has been widely used to study biotissues, as reviewed in Ref. 5. This technique was initially used in ophthalmology,⁶ where it is well developed and clinically used, but it has been continuously benefiting other areas, such as cardiology,⁷ gastroenterology,⁸ dermatology,⁹ and cellular engineering.¹⁰ In dentistry, the first applications were reported

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in 1998,¹¹ having been used for diverse purposes such as characterization of periodontal structures,^{12,13} recurrent caries's detection of and marginal adaptation of restorations,¹⁴ and precocious detection of oral cancer.¹⁵

More recently, besides evaluation of enamel interface restoration,¹⁴ also early caries diagnostics¹⁶ and the analysis of the performance of the dental materials^{17,18} have been studied and reported by our group. In 2006, Kauffman et al. performed the first OCT image of dental pulps using rat's teeth.¹⁹

The key elements of an OCT setup include a broadband light source, whose spectral width limits the axial spatial resolution; an interferometer, which generally employs a Michelson design containing in one of the arms the sample and in the other arm a delay line; and an optical detector, whose signal output is electronically treated and fed to a computer for the image generation. Two domains can be exploited for implementation of an OCT system: the time domain or the spectral domain. In the time domain, the optical delay line arm basically consists of either a movable arm or a Fourier domain delay line.²⁰ In the spectral domain, there are no movable parts in the interferometer arms (except for lateral displacement of the beam on the sample), and the recombined beams from the interferometer are sent to a spectrometer and are Fourier analyzed. It has been shown that spectral domain OCT (SD-OCT) has several advantages over the time domain OCT, including sensitivity²¹ and fast acquisition data, and because the first report on imaging implementation using SD-OCT²¹ it has been widespread.

This work reports the first research comparing images obtained by OCT of the complex dentin-pulp of *in vitro* human teeth, using two different wavelengths in the near infrared, and also using a conical beam tomography as the gold standard. The results are compared, and the conclusion that OCT at ~ 1280 nm performs better than at 850 nm is obtained, besides corroborating the feasibility of OCT for potential clinical use to prevent accidental exposure of the pulp and to promote preventive restoration treatment.

2 Materials and Methods

The experimental study was carried out in accordance with the ethical guidelines in research with human participants by Center of Health Sciences, Universidade Federal de Pernambuco, Brazil.

Higid molar teeth from humans were used in this research. The occlusal surfaces of the teeth were prepared with a perpendicular carbide bur along the axis of the teeth producing a plane on that surface, which were subsequently polished manually with wet 400, 600-, and 1200- water sandpaper sheet with irrigation. Wear was performed perpendicular to the long axis of teeth and lasted until the occurrence of minimal cavity pulpal exposure creating a plane on occlusal surface. The wear stopped until the occurrence of minimal cavity pulpal exposure. In practice, polishing or surface preparation is not required to obtain the images.

To perform OCT imaging of teeth, we used two home-built OCT systems, whose schematic diagrams are shown in Fig. 1. Figure 1(a) shows the schematic of the SD-OCT system operating at the wavelength of 850 nm. The broadband source is a superluminescent diode (Broadband SLD Lightsource S840, SUPERLUM, Moscow, Russia) delivering up to 25 mW and

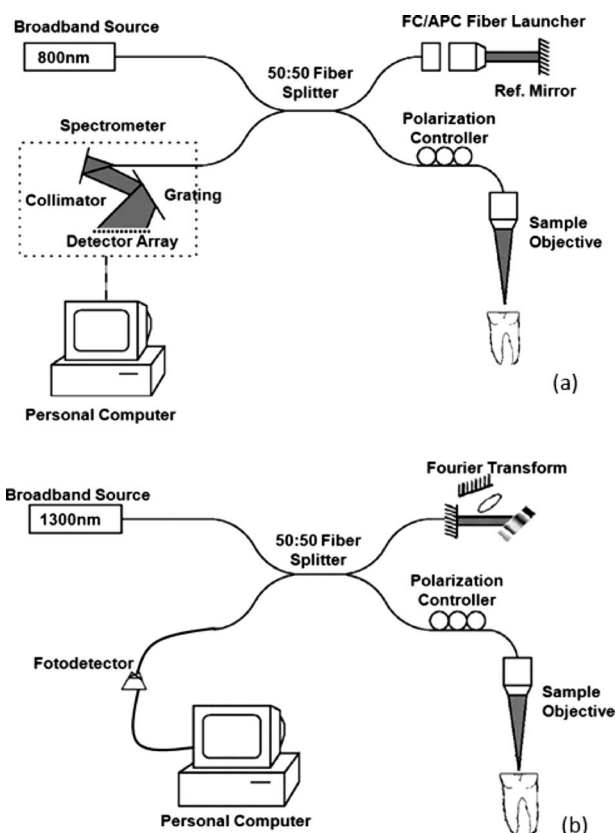


Fig. 1 Schematic diagram of the optical coherence tomography system: (a) SD-OCT operating at 850 nm and (b) time domain OCT operating at 1280 nm with a Fourier domain delay line.

with a 49.9-nm bandwidth, which gives an axial resolution of 6 μm . After traveling through the all-fiber beamsplitter, the reflected beams from the sample and mirror are recombined and sent through a purpose-designed spectrometer consisting of a lens collimator system, 1200-L/mm grating, and CCD (ATMEL, 2048 pixels, 12 bits, California). The maximum incident power on the sample was ~ 5 mW. The output is sent to a personal computer with a LabView-based imaging program.

Figure 1(b) shows the schematic of the time domain OCT system operating at the central wavelength of 1280 nm, maximum average power 5 mW, delivered by a superluminescent diode (model no. SLD-571, SUPERLUM, Moscow, Russia), with a 64.6-nm bandwidth, which represents an axial resolution of 11 μm . As with the system in Fig. 1(a), an all-fiber beamsplitter is used, but in this case the delay line is a Fourier domain delay line²⁰ consisting of a grating and a scanning galvo. The recombined beams are fed into a photodetector and associated electronics, and the output is sent to a personal computer with a LabView-based imaging program.

The images of the remaining dentin thickness and pulp chamber were taken by scanning the occlusal surface in a vestibule-lingual direction. The laser penetrated into the teeth structure and a tomographic image of the frame, parallel to the axis of teeth was obtained.

After the image construction by OCT (1280 and 850 nm), the teeth were tomographically analyzed using the i-CAT®

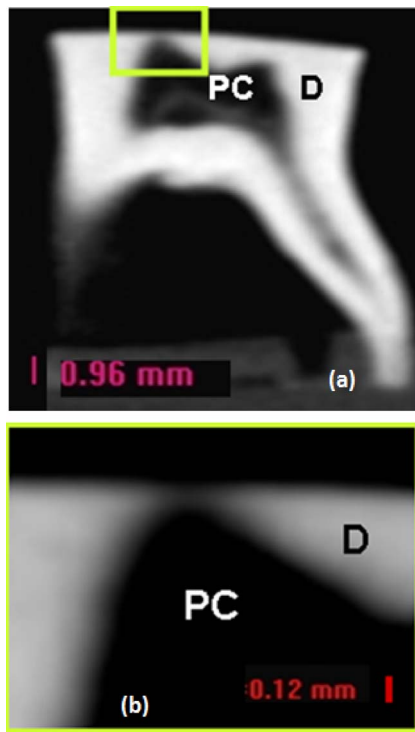


Fig. 2 (a) and (b). i-CAT cone beam volumetric tomography image of the dentin and pulp chamber studied: (a) 0.12 mm slice longitudinal of the tooth and (b) zoom 400% at the dentin-pulp interface.

Cone Beam Volumetric Tomography (CBVT) imaging system (Imaging Sciences International, LLC, Pennsylvania), which radiates from an X-ray source in a cone shape, encompassing a large volume with a single rotation about the sample. This tomography system is a new technology used to analyze both double jaw anatomies in patients by dentistry when more accuracy is required on complementary exams. The CBVT produces volume imaging in an easier and faster way than conventional medical computed tomography.²² The scan offers times at 10, 20, and 40 s, with standard reconstruction taking <30 s, providing dentists with near-instant data for the best possible patient diagnosis, treatment, and surgical predictability. The pictures obtained are then reconstructed using algorithms to produce three-dimensional images at high resolution. Using the i-CAT software, it was possible to generate sliced 2-D images with thickness of 0.12 mm (limited by the instrument resolution), eliminating the problem of superposition, and these images were then compared to the OCT images.

3 Results

For comparison purposes, we first show in Figs. 2(a) and 2(b) images by i-CAT CBVT of the pulp chamber region studied. The white area is the dentin (D) part, whereas the pulp chamber (PC) region is the dark area inside. The square region marked is the zoom region shown in Fig. 2(b). The dimensions in Figs. 2(a) and 2(b) are shown by the scales. Figure 2 shows a remaining dentin thickness of $\sim 120 \mu\text{m}$, which was thick enough to avoid pulpar exposition.

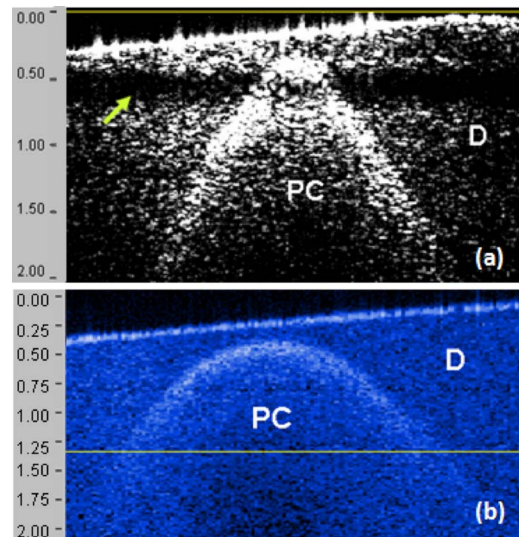


Fig. 3 OCT images of the Dentin (D) and pulp chamber (PC) corresponding to the i-CAT CBVT image of Fig. 2(b): (a) OCT at 1280 nm and (b) OCT at 850 nm. The black transversal region in (a) is an artifact (indicated by the arrow).

The OCT images at the wavelengths of 1280 and 850 nm for the zoomed-in region shown in the i-CAT CBVT image of Fig. 2(b) are seen in Figs. 3(a) and 3(b), respectively, which also show the structural components of the pulp-dentin complex. The structures in the OCT images are distinguished due to the different gray levels (or blue levels, in the case of the 850 nm system), where the contour of the chamber to pulp appears whiter (highest scattered intensities) and the dentin with the darker level (lowest scattered intensity). Those structures are clearly delineated due to influence of the structure of the biological components with distinct refractive indices, which backscatters light in very different ways. No pulp exposition is observed, as confirmed by the i-CAT CBVT, and comparing Figs. 2(b), 3(a), and 3(b), it clearly demonstrates the capacity of quantitative measurement by the OCT with remaining dentin thickness measured as $\sim 120 \mu\text{m}$. Note that the measurements in the OCT value showed on the scale must be divided by the refraction index of dentine ~ 1.5 .¹¹ The black transversal region, indicated by the arrow in Fig. 3(a), is an artifact.

Figure 4 shows an image where the exposition of the pulp cavity is clearly seen. Figure 4(a) is the i-CAT CBVT image cavity, Fig. 4(b) the OCT at 1280 nm, and Fig. 4(c) the OCT at 850 nm. Once again, D and PC are clearly delineated in the OCT image. The pulp exposition site (PE) is seen as a discontinuity at the dentin surface, which is the homogenous white line of high intensity. The OCT images shown allow the direct measurement of the observed region depth.

In order to verify the maximum depth that could be achieved for each OCT system, we carried out a series of measurements whereby the studied dentin region was being reduced by polishing until the pulp could be identified. The scale shown in Figs. 5(a) and 5(b) clearly demonstrate the capacity of quantitative assessment of the OCT, as well as the maximum penetration depth of the radiation inside of the dentin region. Comparing the measurements of the deeper ceiling

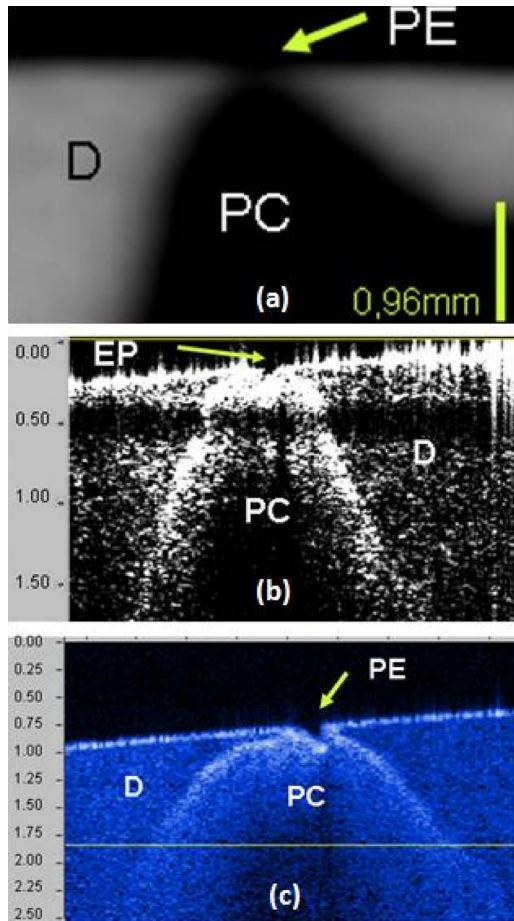


Fig. 4 Dentin (D), pulp chamber (PC), and site of pulpal exposure (PE). (a) i-CAT cone beam volumetric tomography image of pulp-dentin complex, (b) OCT 1280-nm image of pulp-dentin complex, and (c) OCT 850-nm image of pulp-dentin complex.

of the pulp chamber visualized at the two different wavelengths (1280 and 850 nm, respectively), the remaining measured dentin thickness was $\sim 1000 \mu\text{m}$ at 1280 nm and $600 \mu\text{m}$ at 850 nm system. These values had already been corrected for the dentin refractive index ~ 1.5 .¹¹

The deeper penetration depth of the light at 1280 nm compared to 850 nm is due to a remarkable reduction of absorption and scattering coefficients of the dentin at 1280 nm.²³

As a final example, Fig. 6 shows a superposition of three different images from OCT at 1280 nm, taken at the same sample, showing the view of the longitudinal slice detecting cusps (C), D, and the vestibular and palatine pulp horn, where it is possible to identify a remaining thin layer of dentin of roughly 260 and $600 \mu\text{m}$ (PC1 and PC2) between the cavity floor and pulp chamber. This is another clear demonstration of the potential of OCT for pulp chamber assessment.

4 Discussion

Cytotoxicity of the dental material, deep cavity preparation, and accidental exposition of pulp tissue are factors that can be involved with the pulp irritation. The OCT is a new modality of image capable to diagnose the complex dentin pulp and to produce images through the dentin substratum, being able to

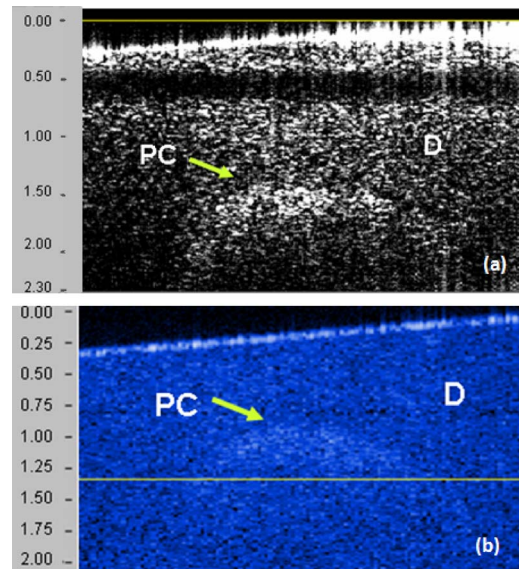


Fig. 5 Image of the deeper pulp ceiling visualized by the OCT. (PC) beginning of the contour of the pulpar ceiling, (D) Dentin: (a) $1000\text{-}\mu\text{m}$ visible depth of the pulp cavity at 1280 nm. The black transversal region is an artifact (b) $600\text{-}\mu\text{m}$ visible depth of the pulp cavity at 850 nm.

measure with precision the distance between the endings of the cavity to pulp chamber. OCT provided images into reminiscent dentinal to pulp cavity of about $1000 \mu\text{m}$ (1280 nm) and $600 \mu\text{m}$ (850 nm) in depth.

Before any restoring procedure, care must be taken to properly evaluate and protect the dentine and the pulp against physical, chemical, and bacterial aggressions. The protection strategies depend basically on the depth of the cavity, the age of the patient, the remaining dentine thickness, and the indicated restoring material. The depth is determined by the remaining dentine thickness between cavity floor and the pulp chamber's ceiling.²⁴ The remaining dentin thickness of $500 \mu\text{m}$ should be enough to protect the pulp tissue against the cytotoxic effects of dental materials,²⁵ and the remaining dentin thickness of $300 \mu\text{m}$ may provoke a persistent inflam-

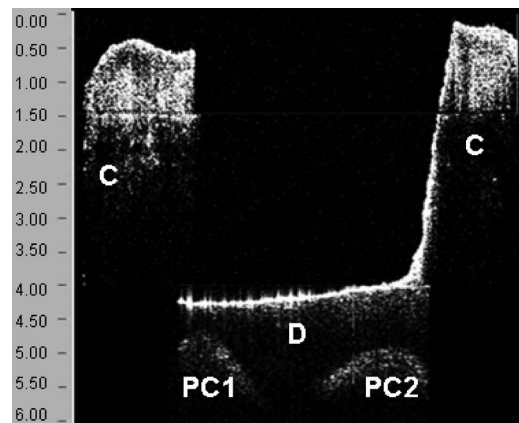


Fig. 6 OCT image superposition showing the dentin (D) and pulp chamber (PC1 and PC2) with wavelength of 1280 nm. Note the thin layer of remaining dentin about $260 \mu\text{m}$ to PC1 and $600 \mu\text{m}$ to PC2.

matory pulpal response. As expected, these results show that the greater the dentin thickness is, the more minor the injuries suffered for the pulp are.²⁶

The OCT is a potential image technique that may contribute to prevent accidental pulp exposures in clinical practice and help pulp protection, by quantitatively determining the remaining dentin, thus helping to make the excavation procedures more predictable and safe.

5 Conclusions

The OCT clearly demonstrate the capacity of quantitative assessment and penetration of the radiation on the pulp chamber and the remaining dentin, compared to the scan in i-CAT CBVT. In accordance with the results presented for the OCTs with a wavelength of 1280 and 850 nm, the two techniques presented effectiveness. Furthermore, our experiment corroborated the depth of penetration almost two times bigger for 1280 nm OCT. OCT is a noninvasive and nondestructive technique; as a consequence, it possesses great potential to be used routinely in clinical practice for the diagnosis of the complex dentin pulp, preventing accidental exposure of the pulp and promoting preventive restoration treatment. For practical use, a hand piece or an appropriate head for the imaging acquisition is required, which is a technologically solvable issue.

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