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Yao-Sheng Hsieh
Yi-Ching Ho
Shyh-Yuan Lee
Chih-Wei Lu
Cho-Pei Jiang
Ching-Cheng Chuang
Chun-Yang Wang
Chia-Wei Sun



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Yao-Sheng Hsieh,^{a,b} Yi-Ching Ho,^c Shyh-Yuan Lee,^{c,d} Chih-Wei Lu,^e Cho-Pei Jiang,^f Ching-Cheng Chuang,^g Chun-Yang Wang,^b and Chia-Wei Sun^{a,b}

^aNational Yang-Ming University, Biophotonics Interdisciplinary Research Center and Institute of Biophotonics, No. 155, Sec. 2, Linong Street, Taipei, Taiwan 112, Taipei, Taiwan

^bNational Chiao-Tung University, Department of Photonics, Hsinchu, Taiwan

^cNational Yang-Ming University, School of Dentistry, Taipei, Taiwan

^dTaipei Veterans General Hospital, Department of Stomatology, Taipei, Taiwan

^eIndustrial Technology Research Institute, Medical Electronics and Device Technology Center, Hsinchu, Taiwan

^fNational Formosa University, Department of Power Mechanical Engineering, Yunlin, Taiwan

^gNational Taiwan University, Institute of Biomedical Engineering, Taipei, Taiwan

Abstract. We characterized and imaged dental calculus using swept-source optical coherence tomography (SS-OCT). The refractive indices of enamel, dentin, cementum, and calculus were measured as 1.625 ± 0.024 , 1.534 ± 0.029 , 1.570 ± 0.021 , and 2.097 ± 0.094 , respectively. Dental calculus leads strong scattering properties, and thus, the region can be identified from enamel with SS-OCT imaging. An extracted human tooth with calculus is covered with gingiva tissue as an *in vitro* sample for tomographic imaging. © 2011 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.3602851]

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1 Introduction

Optical coherence tomography (OCT) was first reported by Fujimoto *et al.*¹ in 1991 and has been widely used in numerical clinical applications, including gastroenterology,^{2–4} ophthalmology,^{5–7} dermatology,^{8,9} and dentistry.^{10,11} In dental science, OCT can be an effective tool for assessing early caries,^{12–14} oral cancer,^{15,16} and periodontal diseases.¹⁷ Periodontitis is one of the major chronic infectious diseases in the oral cavity, and the prevalence of periodontitis is >50% among the population.^{18,19} The World Health Organization revealed that tooth loss resulting from severe periodontitis was found in 5–15% of most worldwide populations in 2003.²⁰ Additionally, recent studies have indicated that certain correlations between periodontitis and various systemic diseases exist.^{21–23} Microbial dental plaque is an etiological factor of periodontitis, and dental calculus is a type of mineralized plaque from deposited microorganisms.²⁴ The traditional diagnosis of subgingival calculus is based on clinical examination using periodontal probing and radiographs. The poor reliability and reproducibility of periodontal probing causes monitoring the progression of periodontal destruction and the effects of treatments to be difficult.^{25–27} Radiography can determine the level of bone-related destruction only for subgingival calculus located on the proximal surface of the teeth because of that x-rays cannot transmit hard tissues. The images of calculus on the buccal and lingual surfaces of a teeth are blocked; thus, it cannot be observed from radiography. In addition, the radiation exposure is accompanied by radiography measurement. Recently, several novel methods have

been developed for dental calculus detection, such as a smart ultrasonic device,^{17,28,29} an LED-based optical probe,³⁰ and laser fluorescence.^{31,32} Raman and laser fluorescence spectrometer may apply to calculus detection but are still under investigation. In fact, the Raman spectrometer is currently used for *in vitro* measurement. *In vivo* measurement is still applied today, but rarely. Laser fluorescence spectrometer should detect calculus using biotracer; however, the sensitivity and reliability are also poor.

Table 1 shows the comparison of general calculus detection methods used today. Compared to these methods, OCT may be an effective tool because it is a noninvasive, nondestructive, non-radiated, and real-time monitoring method. The swept-source optical coherence tomography (SS-OCT) has more benefits than conventional OCT. In this paper, we demonstrate the SS-OCT can be an effective tool for subgingival calculus detection in clinical diagnosis. The refractive indices of enamel, dentin, cementum, and dental calculus were measured for dental tissue characterization. The *in vitro* subgingival calculus was then imaged and processed for contrast improvement. The results show high-quality feasibility of dental calculus diagnosis based on SS-OCT.

2 Experiments and Results

2.1 Swept-Source Optical Coherence Tomography System

An SS-OCT system was built with a 1310-nm swept-source laser (Santec, HSL-2100) as a broadband light source. Figure 1(a) shows the picture of the SS-OCT setup, and Fig. 1(b) illustrates the system scheme. The fiber-based Mach–Zehnder

Address all correspondence to: Chia-Wei Sun, Biophotonics Interdisciplinary Research Center and Institute of Biophotonics, National Yang-Ming University, No. 155, Sec. 2, Linong Street, Taipei, Taiwan 112 Taiwan. Tel: 886228267028; Fax: 886228235460; E-mail: chiaweisun@ym.edu.tw

Table 1 Comparison of calculus detection methods.

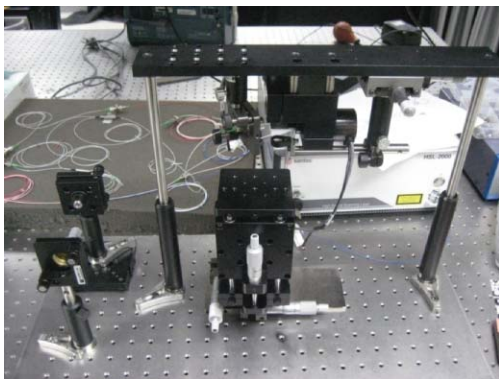
Methods	Advantages	Disadvantages
Radiography ^a	<ol style="list-style-type: none"> 1. Low cost 2. Broad measurement range 	<ol style="list-style-type: none"> 1. Radiative 2. Poor space resolution 3. Calculus that locates on buccal and lingual surface of tooth will embed into tooth image
Dental-CT ^a	<ol style="list-style-type: none"> 1. Broad measurement range 2. 3-D image reconstruction is available 	<ol style="list-style-type: none"> 1. Expensive 2. Real-time images are not available. 3. Radiative 4. Poor space resolution
Intraoral Digital camera	<ol style="list-style-type: none"> 1. Low cost 2. Convenient 3. Nonradiative 	<ol style="list-style-type: none"> 1. Only surface information available
Periodontal probe ^a	<ol style="list-style-type: none"> 1. Convenient 2. Low cost 3. Broad measurement range 	<ol style="list-style-type: none"> 1. Low sensitivity 2. No images 3. Invasive 4. Uncomfortable
Sirona PerioScan (piezoelectric device) ^b	<ol style="list-style-type: none"> 1. Detection of subgingival calculus during ultrasonic scaling 	<ol style="list-style-type: none"> 1. Invasive, uncomfortable 2. Learning curve required
OCT	<ol style="list-style-type: none"> 1. High space resolution 2. Real-time images to differentiate dental structure 3. Nonradiative oral probe was developed 4. 3-D image reconstruction is available 	<ol style="list-style-type: none"> 1. Limited penetration depth
SS-OCT ^{c-e} (compare to other OCT)	<ol style="list-style-type: none"> 1. Higher imaging speed 2. Higher detection efficiency 3. Higher sensitivity 4. Simpler 5. Better SNR with suitable filter 	<ol style="list-style-type: none"> 1. Expensive 2. Very high speed data acquisition interface is necessary
Raman spectroscopy ^{f-h}	<ol style="list-style-type: none"> 1. High sensitivity 2. Simple sample preparation 3. Easy spectral analysis 4. Responses to mineral and chemical concentrations are available 	<ol style="list-style-type: none"> 1. <i>In vitro</i> experiment only 2. Expensive 3. No images
Laser fluorescence spectrometer ^{i,i}	<ol style="list-style-type: none"> 1. Real time detection 2. Responses to bacteria and chemical concentrations are available 3. Easy spectral analysis 	<ol style="list-style-type: none"> 1. <i>In vitro</i> experiment 2. No images

^aReference 17.^bReference 33.^cReference 34.^dReference 35.^eReference 36.^fReference 37.^gReference 38.^hReference 39.ⁱReference 31.ⁱReference 32.

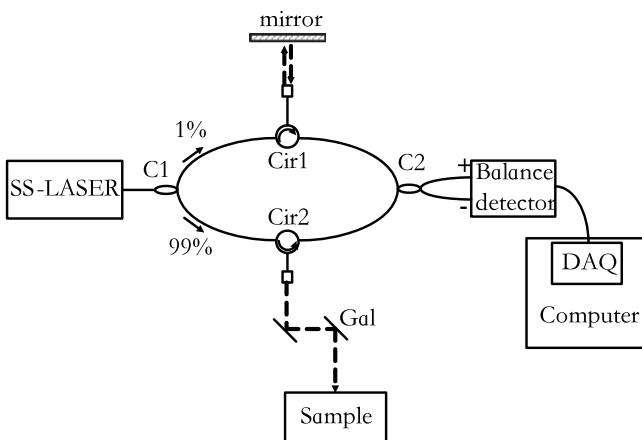
interferometer was adopted with two couplers (one is 99:1, and the other is 50:50), and two optical circulators. The illumination power of the sample arm was 0.8 mW, and the power of the reference arm was 0.6 μW. The balance detector was utilized for interference detection, and the data acquisition card (DAQ card, NI-PCI 5122) was then used for computer-photodetector interfacing. In our *in vitro* study, all samples were placed on a three-dimensional translation stage for optical scanning. The wavelength-scanning rate is 20 kHz. The frame rate is 20 Hz (1000 A-scans/frame). The electric signals acquisition rate is 100 MS/s by NI-PCI 5122. Experimental data were collected and analyzed using LabVIEW (National Instrument) software. Dispersion compensation and interpolation were also completed using LabVIEW. We saved the OCT images per 100 μm length. Because of the width of the tooth being ~1.2 cm, around 120 images were observed. For imaging the whole tooth, 200 images were taken in the experiments.

2.2 Refractive Indices Measurement

The refractive index determines the optical property of material. In previous studies,^{40,41} the refractive index of a highly scattering sample could be estimated from OCT measurement (as



(a)



(b)

Fig. 1 (a) Inrange of SS-OCT system and (b) schematic diagram of SS-OCT system. C1: 99:1 fiber coupler; C2: 50:50 fiber coupler; Cir1, Cir2: optical circulators; Gal: galvanometer.

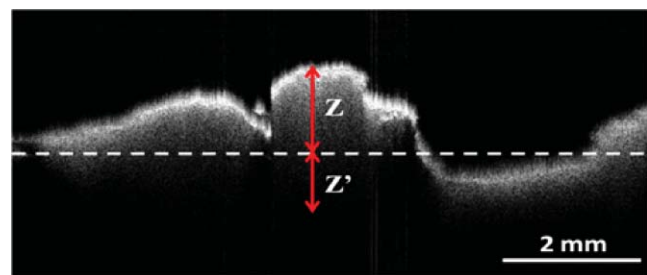
Table 2 Refractive indices of dental tissues and glass slide.

	Refractive index
Enamel	1.619 ± 0.034
Dentin	1.528 ± 0.026
Cementum	1.567 ± 0.030
Calculus	2.112 ± 0.127
Glass slide	1.503 ± 0.018

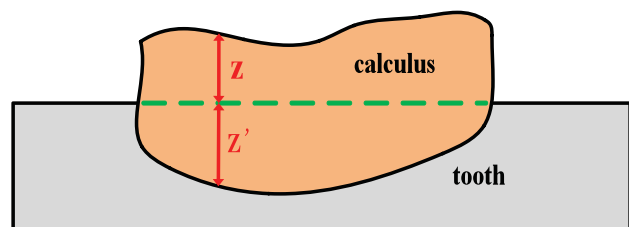
shown in Fig. 2). The lengths of the upper and lower parts are defined as *z* and *z'* and the refractive index is

$$n = 1 + \frac{z'}{z}$$

The refractive indices of enamel, dentin, and cementum were calculated following the method of Ref. 40. For calculating the refractive index of calculus, some clear definition of boundaries of *z* and *z'* should be discussed because the lower boundary of *z'* should choose a line that light can pass through as easily as possible. We chose three boundary lines in the OCT image for defining the boundary of refractive index calculation. The upper line is the top of the calculus. The middle line is the extension of the tooth surface from the left side to the right side of the calculus. The bottom line is the line that passes through the lower boundary of the calculus. Therefore, the chosen line that locates the bottom of the enamel instead of the bottom of the calculus is not easy to define in the real margin. Figure 3 shows the OCT images of glass, enamel, dentin, and cementum samples. Each sample was polished as a thin slice for



(a)



(b)

Fig. 2 (a) SS-OCT image of dental calculus and (b) scheme of dental calculus.

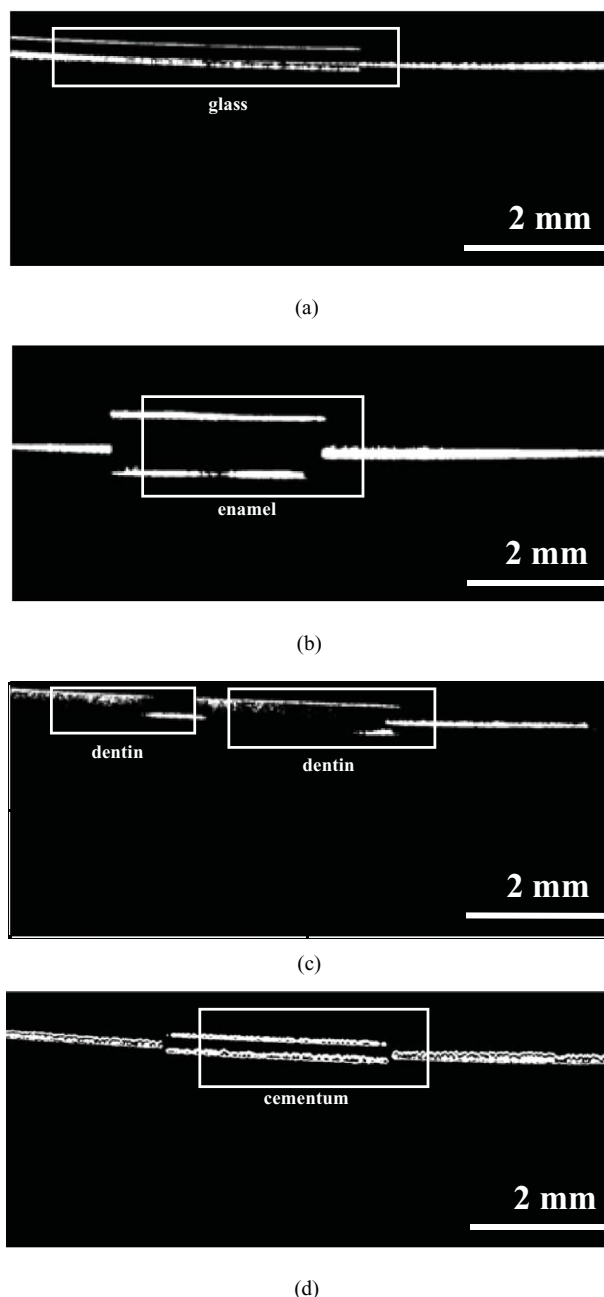


Fig. 3 SS-OCT images of (a) glass, (b) enamel, (c) dentin, and (d) cementum.

SS-OCT measurement. All the OCT images were processed with a Gaussian filter and then binarized for contrast improvement. A (2×6)-mm glass slide was used as a standard sample for refractive index measurements calibration because its refractive index is well known. To avoid multireflection, the glass slide was placed on a (3×8)-mm rough-surfaced aluminum bar. Figure 3(a) is the OCT image of the glass slide. To observe the refractive index, we chose 20 points for each sample and five samples were measured in the OCT image of the glass slide for calculation. The refractive index of the glass slide is 1.503 ± 0.018 and extremely close to the typical glass refractive index of 1.52.⁴² Table 2 lists the refractive indices of enamel, dentin, cementum, calculus, and the glass slide, which were each measured as 1.625 ± 0.024 , 1.534 ± 0.029 , 1.570 ± 0.02 ,

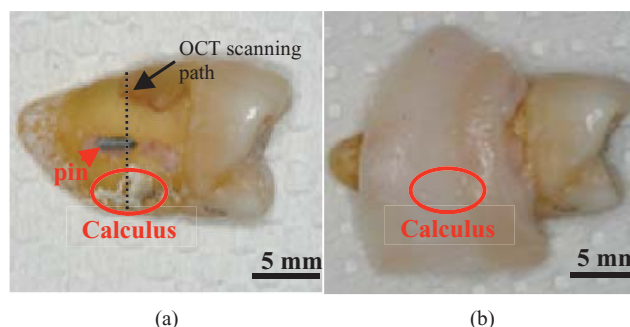


Fig. 4 (a) Dental calculus sample and (b) gingival tissue covered on the sample of dental calculus.

2.097 ± 0.094 , and 1.503 ± 0.018 , respectively. These measurements strongly agree with previous results.⁴¹

2.3 In Vitro Dental Calculus Imaging

Figure 4 demonstrates the *in vitro* sample of dental calculus. One human caries-free tooth with subgingival calculus, extracted for periodontal reasons, was enrolled. The calculus region was marked on the surface of the tooth. For feasible study of subgingival calculus detection, a piece of porcine gingiva tissue with 0.8-mm thickness was used to cover the tooth sample. For effective position alignment, the tooth was fixed on beeswax and attached to a platform before applying gingiva to the tooth. Furthermore, an iron pin was placed on the surface next to the calculus to ensure the same measurement location because the iron pin shows an obviously high reflection property in the OCT image. The measurement path that passes through the pin for alignment subject is shown in Fig. 4. We moved the platform at 100 μm between images; hence, measuring at the same location was possible if the platform moved in a reverse direction at the

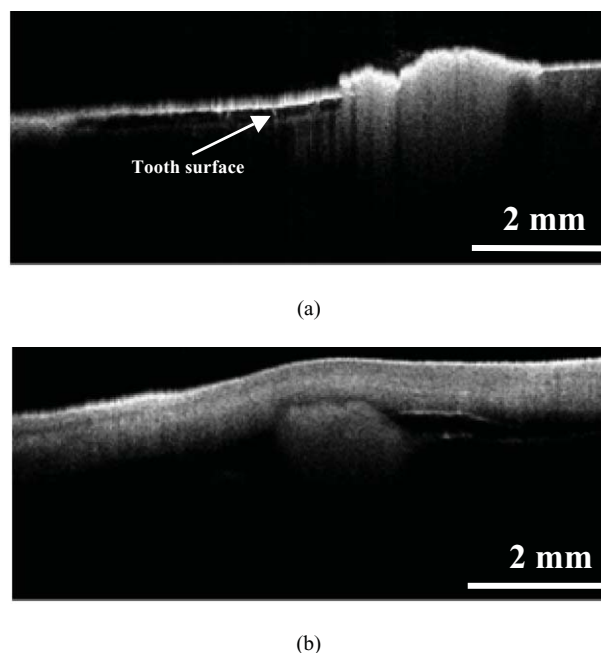
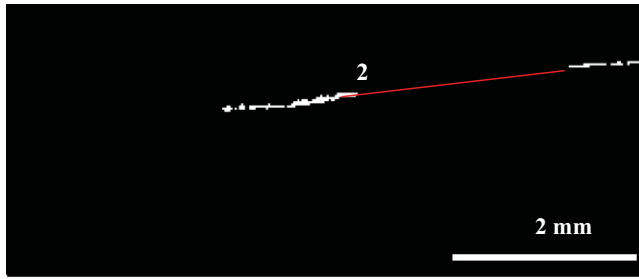
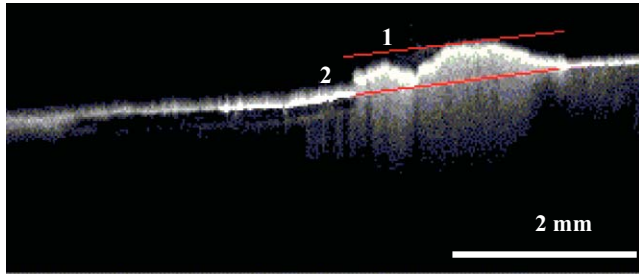


Fig. 5 (a) OCT image of dental calculus and (b) OCT image of subgingival calculus.



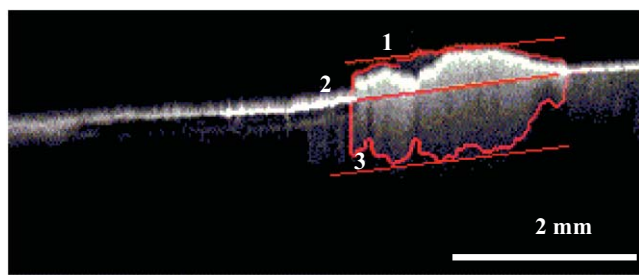
(a)



(b)



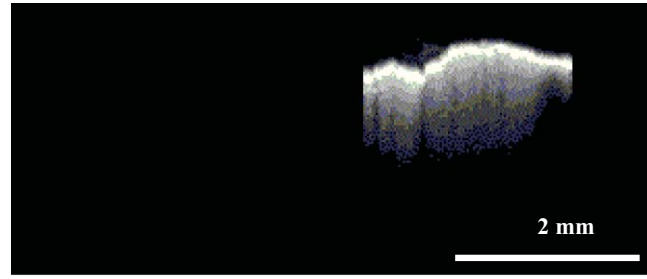
(c)



(d)

Fig. 6 Image process for lines decision: (a) Removing the calculus and keeping the tooth surface for second line drawing, (b) the first line drawing, (c) the margin detection of calculus, and (d) the third line drawing and boundaries of refractive index calculation.

same distance after applying gingiva to the tooth. Therefore, images with the same number show a favorable comparison. We also controlled where the pin image is displayed in OCT images to ensure that the entire experiment began at the same location and that the OCT calculus images allowed for an effective comparison. Figure 5 shows the OCT images of the sample with respect to Fig. 4. By scanning along the path (the dotted line in Fig. 4), the OCT images of normal tooth surface and calculus can be observed in Fig. 5. Figure 5(a) shows the calculus region that corresponds to Fig. 4(a), and Fig. 5(b) demonstrates the



(a)



(b)



(c)



(d)

Fig. 7 The calculus region with threshold filtering: (a) original image, (b) 0.01 threshold value processing, (c) 0.3 threshold value processing, and (d) 0.18 threshold value processing.

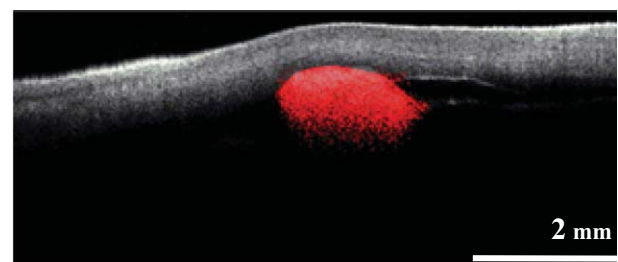


Fig. 8 Postprocessed subgingival calculus image.

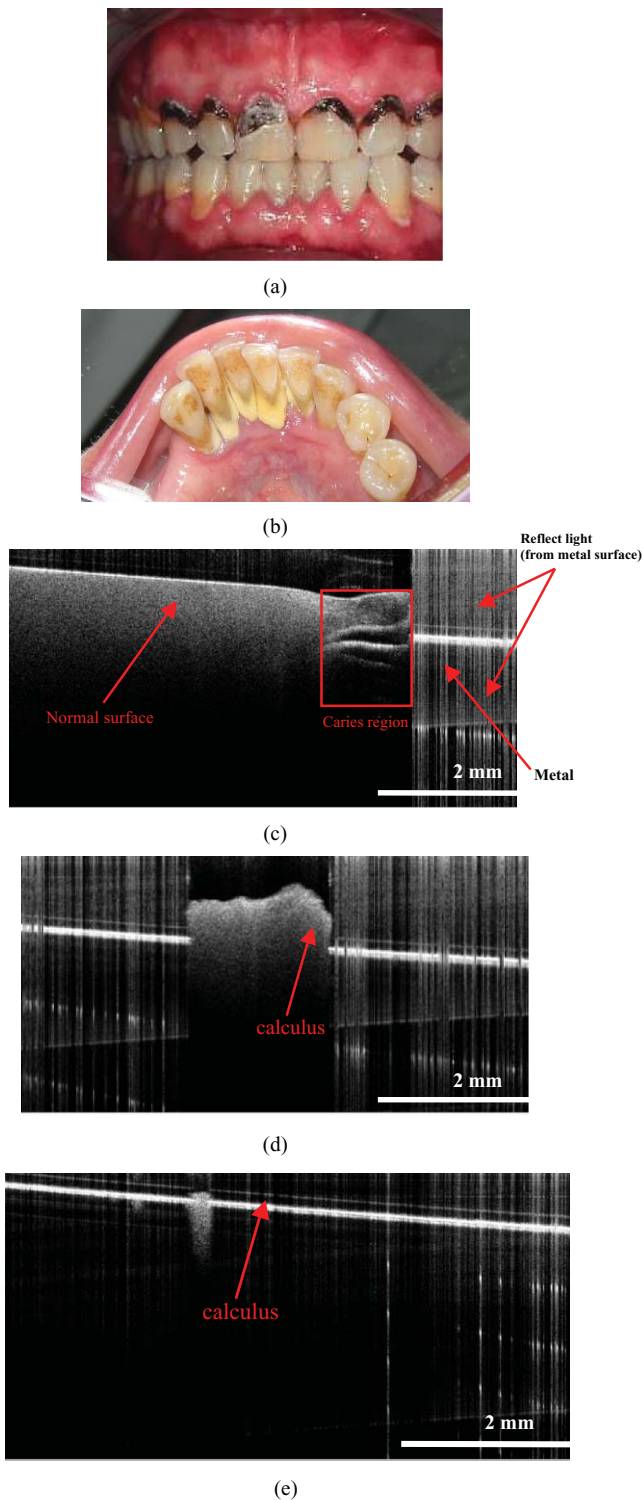


Fig. 9 (a) Images of caries and (b) calculus deposition on lingual side of mandibular incisors. (c) OCT image of caries, (d) OCT image of calculus, and (e) OCT image of grinded calculus.

subgingival calculus image that corresponds to Fig. 4(b). Although the gingival layer attenuates the optical signal, the calculus region can also be seen in Fig. 5(b).

Before the determination of refractive index, three boundary lines should be given. The measured image was postprocessed

with an anisotropic diffusion filter, midvalue filter, and threshold filter for noise suppression and identified the position of calculus edge.⁴³ These processes were also used for determining the boundary lines. Because of the surface of teeth can be observed directly from the OCT image, the second line was decided first. In Fig. 6(a), we had removed other parts except teeth surface and approach the second line. The threshold filter and Gaussian filter were used to remove the calculus and keep the tooth surface. As shown in Fig. 6(a), we kept tooth surface and connected two ends of the surface as the second line. The first line was decided as a parallel to second line and pass through the top point of calculus [Fig. 6(b)]. Next, the edge filter was used to obtain the calculus margin. In Fig. 6(c), we found the lowest point of calculus margin and decided the third line passes through the point with parallel to the other lines. This approach provides an easy way to estimate the refractive index for dental tissue characterizing. The boundaries of z and z' are indicated in Fig. 6(d).

For optimization of image process, we separated calculus image with threshold and Gaussian filters. Figure 7 shows the processed images with different threshold values. Obviously, the processed calculus size depends on the threshold value in the gray-scale threshold filter. We chose the threshold value trial and error for imaging optimization.^{44–46} The optimal threshold value is 0.18. Because the parameters of OCT operation and image process are set as the optimal values, the errors of linear approximation can then be reduced. In clinical diagnoses, the OCT image provides great assistance if the dental calculus region can be highlighted accurately. The dental calculus region can be featured after this processing. Figure 8 shows the processed subgingival calculus image, and the calculus region is marked in red.

3 Discussion and Conclusion

Although many studies have reported that caries detection could be achieved based on OCT imaging, we demonstrate a method that can be applied to subgingival calculus detection in dentistry. Moreover, the refractive index of dental calculus was measured in experiment. The dental calculus shows different optical and image properties to the caries. In Fig. 9, we can find that the dental calculus shows different optical and image properties to the caries. The caries reveal lower group delay and destroy the tooth structure inwardly. On the other hand, the calculus shows stronger group delay and do not affect the tooth structure because the calculus always deposits on the tooth surface. The different features can be observed in OCT images. Figure 9(e) shows the small volume of calculus still reveals the same property of strong group delay. Therefore, the difference between caries and calculus can be diagnosed by direct OCT imaging. In clinical diagnoses, the method presents advantages when compared to conventional x-ray imaging. X-ray imaging is radioactive and cannot observe the calculus on the buccal or lingual surface of the tooth. However, OCT imaging can overcome these two drawbacks. For further study, an oral probe will be developed instead of the sample arm for *in vivo* measurement.

A linear boundary approximation method was used in this paper for refractive index calculation. This method provides an estimation of refractive index fast and easy. Errors of linear approximation occur with rough surface and nonlinear boundary

of dental tissue. However, it should be sufficient for understanding the characterizations of teeth and calculus in our experiment.

We demonstrated the subgingival calculus detection method using SS-OCT at 1310 nm with a Mach-Zehnder interferometer. The refractive indices of tooth tissue as enamel, dentin, cementum, and calculus were 1.625 ± 0.024 , 1.534 ± 0.029 , 1.570 ± 0.021 , and 2.097 ± 0.094 , respectively. Calculus revealed a strong scattering property that originated with a high refractive index. For subgingival calculus imaging, a human tooth with 0.8 mm porcine gingiva was employed as an *in vitro* sample in the experiment. The dental calculus region could then be marked with the postprocess. The experimental results indicate that the SS-OCT can be of great assistance for dental calculus detection. Currently, the handheld probe is under development for further *in vivo* study.

Acknowledgments

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