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Abstract. This study aimed to investigate swept source optical coherence tomography (SS-OCT) as a detecting tool for occlusal caries in primary teeth. At the *in vitro* part of the study, 38 investigation sites of occlusal fissures (noncavitated and cavitated) were selected from 26 extracted primary teeth and inspected visually using conventional dental equipment by six examiners without any magnification. SS-OCT cross-sectional images at 1330-nm center wavelength were acquired on the same locations. The teeth were then sectioned at the investigation site and directly viewed under a confocal laser scanning microscope (CLSM) by two experienced examiners. The presence and extent of caries were scored in each observation. The results obtained from SS-OCT and conventional visual inspections were compared with those of CLSM. Consequently, SS-OCT could successfully detect both cavitated and noncavitated lesions. The magnitude of sensitivity for SS-OCT was higher than those for visual inspection (sensitivity of visual inspection and SS-OCT, 0.70 versus 0.93 for enamel demineralization, 0.49 versus 0.89 for enamel cavitated caries, and 0.36 versus 0.75 for dentin caries). Additionally, occlusal caries of a few clinical cases were observed using SS-OCT *in vivo*. The results indicate that SS-OCT has a great detecting potential for occlusal caries in primary teeth. © *2014 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JBO.19.1.016020]

Keywords: optical coherence tomography; primary teeth; occlusal caries; detection; sensitivity; specificity.

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1 Introduction

Tooth surfaces with pits and fissures are particularly vulnerable to caries development.[1] With the permanent dentition, caries involving the occlusal surfaces account for almost 60% of the total caries experience in children and adolescents.[2] Meanwhile, primary teeth have less acid resistance than permanent teeth and lesion progression in primary teeth is faster than in permanent teeth.[3] The large dentin lesions beneath seemingly sound occlusal caries are being observed more frequently in children;[4] the prevalence of these noncavitated lesions has been reported to be around 15% but could be as high as 50%.[5,6] The term "hidden caries" refers to the subtype of occlusal pit and fissure caries under apparently noncavitated opaque enamel in mostly permanent dentition, which is attributed to the fluoride uptake by the superficial enamel.[1,2] Prevalence of hidden caries in primary dentition is also reported in 12% of young children; the condition presents the dentist with challenges in diagnosis and treatment planning.[7]

The rapid progression of carious lesion toward the pulp in primary teeth would eventually lead to the infection of dental pulp when left untreated.[8,9] Additionally, diagnosis can be difficult in very young children where the clinical signs and symptoms may be less reliable.[10] Hidden occlusal caries lesions are prominent even in low- and moderate-caries-risk patients,[11] hence it is important for clinicians to detect and characterize these lesions with accuracy and as early as possible in primary dentition.

Optical coherence tomography (OCT) is a noninvasive diagnostic method that allows micron-scale imaging of biologic tissues over small distance.[12–14] It was introduced in 1991[12] and uses infrared light waves that reflect off the internal microstructure in a way that in principle is analogous to ultrasonic pulse-echo imaging. By coupling a low coherence light into a Michelson interferometer, the light split to the sample arm and a reference mirror. When reflections from the reference mirror and backscattered light from the tissue are recombined, an interference signal is detected within the coherence length of the source. A series of these optical signals can then be interpreted to create two-dimensional (2-D) images, and serial 2-D scans can create three-dimensional images.

In the dental field, the potential of OCT has been explored for decayed tooth structure, such as caries, crack, and fracture.[15–19] Generally, the ability of OCT to evaluate demineralization is perceived to be based on two main principles: multiple scattering of the incident beam in the demineralized tissue due to increased porosity, and light depolarization by the demineralized dental tissue. A polarization sensitive (PS) OCT setup

can reconstruct images from the backscatter signal exclusively using the perpendicular (or cross-) polarization axis while in conventional (or nonPS) OCT setups, a depolarization signal cannot be obtained separately. Both conventional and cross-polarization (CP) swept source (SS)-OCT systems have shown potential for clinical imaging[20,21] owing to their improved imaging speed compared to the former time-domain systems. However, to our knowledge, there is relatively little research on the validity of occlusal caries detection and diagnosis in primary teeth using OCT, particularly when a system without polarization sensitivity is employed.

The aim of this study was to assess SS-OCT as a diagnostic tool for the detection of occlusal caries and hidden lesion in primary teeth. The results of SS-OCT *in vitro* were compared with those of visual inspection and direct observation of sectioned samples under confocal laser scanning microscope (CLSM) as the validation method. Occlusal caries of primary teeth *in vivo* were also imaged in real clinical situation using SS-OCT.

2 Materials and Methods

Extracted human primary molar teeth with/without occlusal caries stored at 4°C in distilled water containing a few thymol crystals were used. The usage of the teeth was approved by the Institutional Review Board of Tokyo Medical and Dental University (Nos. 578 and 599). Twenty-six primary teeth were selected and up to three locations on the occlusal pits and fissures including intact zone were arbitrarily chosen on each tooth (12 noncavitated teeth and 14 cavitated teeth). In total, 38 locations were examined in this study. The examiners who took part in this study were six dentists (examiner YN, YS, AS, IW, MM, and JT), with experience in OCT image interpretation. In order to reach a consensus on the diagnostic criteria of SS-OCT diagnosis, the reference examiner (YN) discussed SS-OCT imaging with other examiners during a 1-h session using approximately 25 extracted teeth that were not included in the main study. The display settings, such as brightness and contrast, were the same for all images and examiners. All the examiners were blind to the selection of investigation sites and to the other examiners' scoring results. Visual examination and SS-OCT evaluations were performed in separate sessions and after shuffling the order of appearance for each case to ensure there was no interference from the previous observations.

2.1 Visual Examination

After cleaning and drying the tooth surface, a photograph was taken of the investigation site using a digital single-lens reflex camera (Nikon D50, Nikon, Tokyo, Japan) equipped with an auto focus 90-mm lens (Tamron SP AF 90 mm, Saitama, Japan). The digital image was displayed on a computer screen at an approximate final magnification level of 10×. The sites to be investigated in each tooth were clearly marked by a red circle drawn on the digital image. All the visual examiners performed their blinded assessments of the lesion extent at the investigation site on the monitor and scored them as follows:[16]

0: Sound tooth surface. No evidence of caries or demineralization of enamel.

1: Enamel demineralization but without cavitation. Opacity or discoloration (white or brown) is visible at the entrance to the pit or fissure.

2: Localized enamel breakdown due to caries with no visible dentin or underlying shadow.

3: Dentin caries. Underlying dark shadow from dentin and distinct cavity with visible dentin.

2.2 SS-OCT System and Cross-Sectional Imaging of Occlusal Fissures

The SS-OCT system (Prototype 2; Panasonic Healthcare Co. Ltd., Ehime, Japan) is a Fourier domain (FD) technique that measures the magnitude and time delay of reflected light (Fig. 1). In this system, the center wavelength is 1330 nm (bandwidth 110 nm) with a 30-kHz sweep rate. The system is equipped with a hand-held probe with power of <10.0 mW,

Fig. 1 The swept source optical coherence tomography (SS-OCT) system used in this study. (a) An overview of the SS-OCT machine including screen, interferometer, scanning laser source, and data processing PC. (b) A hand-held probe of the SS-OCT.

specifically designed for intraoral imaging. The probe also includes a complementary metal-oxide semiconductor (CMOS) camera that enables real-time photographic observation of the surface being scanned by the OCT beam. The focused light beam is projected onto the subject and scans the plane of interest. The backscattered light from the sample is coupled back to the system and digitized according to time; it is then analyzed in the FD to determine the depth information of the specimen. This creates 2-D images in conjunction with the beam scanning. Although the spot size of the laser beam is 20 μm (lateral resolution), the axial resolution of the system is 12 μm in air, which corresponds to 8 μm in tissue assuming a refractive index of approximately 1.5. A 2000 × 1019 pixel image can be the output within 0.3 s including data acquisition and processing time. The hand-held scanning probe connected to the SS-OCT was set at a fixed distance over the occlusal fissures, with the scanning beam oriented 90 deg with respect to the tooth occlusal plane. SS-OCT images were obtained from the 38 selected sites, where the visual inspection had been performed. The investigation sites were then classified and scored as follows:[16]

0: No caries. Obtained OCT signal was the same level and shape as that of intact enamel and loss of enamel surface did not occur.

1: Superficial demineralization of enamel. OCT signal intensity was enhanced within the enamel zone but loss of enamel surface did not happen.

2: Enamel breakdown due to caries. The enamel surface became discontinuous at the occlusal fissure. Increased OCT signal occurred within the enamel.

3: Dentin caries. An intensified OCT signal was obtained beyond the dentin–enamel junction (DEJ) with or without enamel loss.

2.3 CLSM Observation

The verification for diagnosis was determined by the reference examiner through direct observation of the sectioned fissures using CLSM (1LM21H/W; Lasertec Co, Yokohama, Japan). For this purpose, two points along the OCT imaging plane were marked on the tooth surface using marker pen under the CMOS camera imaging. The tooth was then cross-sectioned parallel to the OCT imaging plane using low-speed diamond saw (Isomet, Buehler, Lake Bluff, Illinois), and the cross section was further trimmed using silicon carbide papers to reach a section through both marked points. Finally, the surface was polished with diamond paste down to 3 μm in particle size under running water. Totally 38 polished surfaces were examined for direct viewing under CLSM at magnification level of 100×. The investigation site was scored according to the following criteria:

0: No caries. No enamel demineralization.

1: Superficial demineralization of enamel but without cavitation. Loss of enamel surface did not happen.

2: Enamel breakdown due to caries within the enamel thickness.

3: Dentin caries. Demineralization or morphological changes beyond DEJ with or without loss of enamel surface.

Two examiners with sufficient experience in histopathological study of caries carried out observation of the polished surfaces. All the sites were jointly investigated by the two examiners and the consensus score was reached in the following discussion.

2.4 Statistical Analysis

Statistical analysis was performed using a statistical software package (MedCalc Software ver 12.7, Ostend, Belgium). Sensitivity and specificity indices in each diagnostic threshold (enamel demineralization, score 0 versus 1 to 3; enamel caries, score 0 to 1 versus 2 to 3; dentin caries, score 1 to 2 versus 3) were calculated from the detecting results of visual inspection and SS-OCT. Using these indices, receiver operating characteristic (ROC) analysis was also performed by DeLong's method (nonparametric test) and the area under the curve (known as Az value) was calculated.[22]

2.5 Clinical Examination

In addition to the *in vitro* study, noncavitated occlusal caries of clinical cases were also observed using SS-OCT on three primary posterior teeth. This *in vivo* study was also approved by the Ethics Committee of the Tokyo Medical and Dental University and was conducted in accordance with the Declaration of Helsinki. The study included three healthy children, who were 5 years of age (two males and one female) and had come to the dental hospital to treat their decayed teeth. After the study protocol had been explained in detail, signed and informed consent was obtained from each child's parents. In these subjects, dentin caries underneath the overlying enamel was evident from the clinical examination aided by the radiographs, which were captured from the buccal side by a bisected angle technique as routine examination.[21]

The teeth were cleaned using a brush cone attached to a low-speed handpiece. Photographs of the occlusal surface from the occlusal view were taken using a digital camera. After taking photographs, cross-sectional imaging of the area was performed in 2-D using the SS-OCT hand-held probe [Fig. 1(b)]. The lesions were then excavated according to the clinical protocol; before restoring with a resin composite, images of the cavitated occlusal surface were obtained in order to confirm the extent of carious damage.

3 Results

The results and values of sensitivity, specificity, and area under ROC curve (Az) for the detection in each diagnostic threshold derived from the *in vitro* study are presented in Table 1. After obtaining the CLSM images, the 38 surfaces included in the *in vitro* study were classified as 10 intact surfaces, 6 enamel demineralization, 10 enamel caries, and 12 dentine caries. The resulting *in vitro* images of occlusal pits and fissures are shown in Figs. 2–4. In the grayscale OCT images that were reconstructed according to the signal intensity, the demineralized area appeared as a brighter zone because of the increased SS-OCT signal intensities. On the other hand, the signal intensity from the cavitated dentin lesion underneath intact enamel was weaker and formed a relatively dim image (Fig. 3). In Fig. 4, the two distinct lines along enamel were observed which turned out to be the neonatal line and DEJ.

The sensitivity values of SS-OCT were higher than those of visual inspection: 0.93 for enamel demineralization, 0.89 for

Table 1 Sensitivity, specificity, and *Az* value of receiver operating characteristic (ROC) analysis in each diagnostic threshold obtained from fix examiners.

Visual examination			
Sensitivity examiner	0 versus 1 to 3	0 to 1 versus 2 to 3	0 to 2 versus 3
1	0.43	0.23	0.08
2	0.82	0.32	0.17
3	0.68	0.55	0.67
4	0.64	0.36	0.33
5	0.82	0.68	0.33
6	0.82	0.82	0.58
Mean	0.70	0.49	0.36
SD	0.15	0.23	0.23
Swept source optical coherence tomography (SS-OCT)			
1	0.96	0.86	0.67
2	0.93	0.82	0.83
3	0.86	0.82	0.58
4	0.89	0.86	0.50
5	1.0	1.0	0.92
6	0.96	0.96	1.0
Mean	0.93	0.89	0.75
SD	0.05	0.08	0.20
Visual examination			
Specificity examiner	0 versus 1 to 3	0 to 1 versus 2 to 3	0 to 2 versus 3
1	1.0	1.0	1.0
2	1.0	1.0	1.0
3	0.90	0.81	1.0
4	0.90	0.94	1.0
5	0.90	1.0	1.0
6	0.60	0.75	0.96
Mean	0.88	0.92	0.99
SD	0.15	0.11	0.02
Swept source optical coherence tomography (SS-OCT)			
1	1.0	0.94	1.0
2	1.0	1.0	1.0
3	1.0	0.81	0.96

Table 1 (*Continued*).

Visual examination			
Specificity examiner	0 versus 1 to 3	0 to 1 versus 2 to 3	0 to 2 versus 3
4	1.0	0.75	0.92
5	0.80	0.69	0.69
6	0.80	0.81	0.88
Mean	0.93	0.83	0.91
SD	0.10	0.12	0.12
Visual examination			
Az of ROC examiner	0 versus 1 to 3	0 to 1 versus 2 to 3	0 to 2 versus 3
1	0.71	0.61	0.54
2	0.91	0.66	0.58
3	0.79	0.68	0.83
4	0.77	0.65	0.67
5	0.86	0.84	0.67
6	0.71	0.78	0.77
Mean	0.79	0.70	0.68
SD	0.08	0.09	0.11
Swept source optical coherence tomography (SS-OCT)			
1	0.98	0.90	0.83
2	0.96	0.91	0.92
3	0.93	0.82	0.77
4	0.95	0.81	0.71
5	0.90	0.84	0.80
6	0.88	0.88	0.94
Mean	0.93	0.86	0.83
SD	0.04	0.04	0.09

cavitated enamel lesions, and 0.75 for dentine caries. Specificity for SS-OCT was 0.93 for enamel demineralization, 0.83 for cavitated enamel lesions, and 0.91 for dentine caries, whereas those for visual inspection were 0.88, 0.92, and 0.99, respectively. Considering the obtained area under the ROC curve, detection rates at all cut-off values (i.e., enamel demineralization, cavitated enamel caries, and dentin caries) for SS-OCT were higher than those of visual inspection.

Among dentin caries cases of *in vitro* study, six hidden caries lesions were detected (Fig. 3). The sensitivity was 0.21 for visual inspection and 0.88 for SS-OCT, whereas the specificity was 1.0 for visual inspection and 0.92 for SS-OCT. ROC analysis of SS-OCT showed higher *Az* value than those of visual inspection (Table 2).
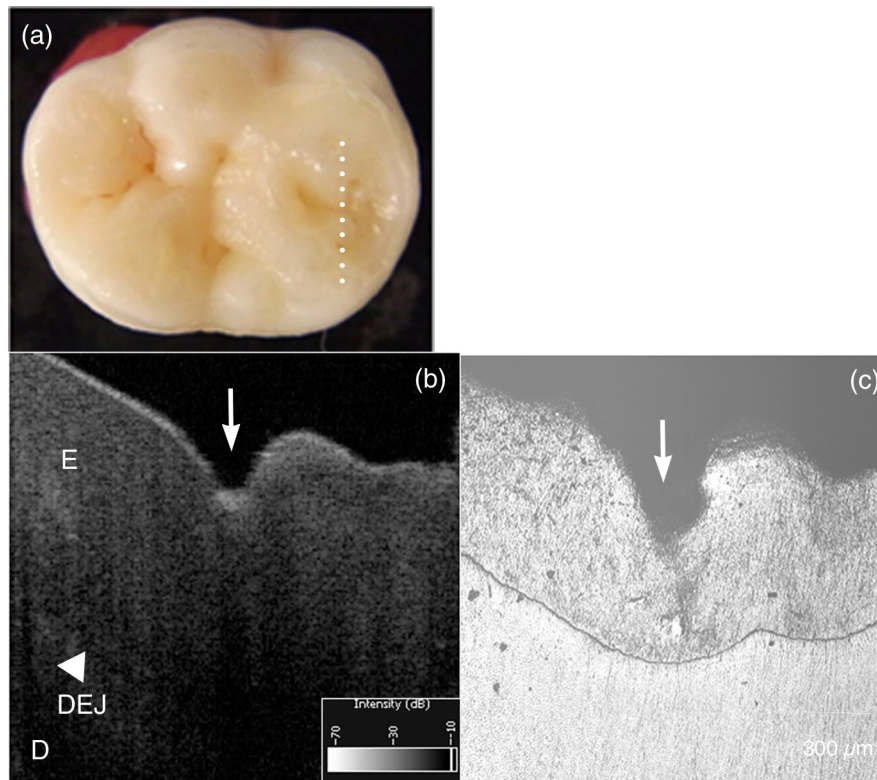
Fig. 2 Images obtained from the occlusal fissure including visibly no cavitation, where the visual detection was enamel demineralization without cavitation. (a) SS-OCT scan was performed along the white dotted line before sectioning the tooth. In the photograph, yellow or brown discoloration could be seen on the primary occlusal surface. (b) Visually intact part indicated no loss of surface (cavitation) in that area. However, SS-OCT image showed a bright surface reflection (arrow), and SS-OCT signal from the deeper enamel and dentin–enamel junction (DEJ) was stable (score 1). The intensity scale is shown in black and white in decibel (db). E, enamel and D, dentin (c) In the CLSM observation, slight demineralization of enamel was observed as a dark enamel structure. The score of this site was 1 according to CLSM.

Representative images of the occlusal surfaces and their caries of *in vivo* study are shown in Fig. 5. The cavities of three subjects had reached into dentin, and in SS-OCT images, the reflection signal intensified beyond the DEJ depth indicating the presence of dentin caries.

4 Discussion

In our *in vitro* study, 38 locations of occlusal fissure including six enamel demineralization and 22 caries involving six hidden lesions were observed using SS-OCT. SS-OCT could detect the enamel demineralization as bright lesions with intensified backscattered signals (Fig. 2) in this study. The highlighting zone in SS-OCT image corresponds well with the demineralized area in the cross-sectioned CLSM results; sensitivities of SS-OCT for the detection of enamel demineralization, enamel cavitated caries, and dentin caries were higher than those of visual inspection. Several lines of evidence showed high sensitivity values for fluorescence-based devices (including both laser or LED) that detect lesions according to the fluorescent nature of progressed lesions; however, all these devices showed low specificity in occlusal caries in several studies.[23–25] In our study, the SS-OCT provided a clear image of lesions ranging from early enamel to deep dentin caries at occlusal pits and fissures, with comparatively high specificity caries.

It is well documented that the refraction of light occurs between two homogeneous media with different refractive indices.[19,26] In SS-OCT images of the sound tissue, the limits of enamel appear as whiter (high backscattered signal intensity) due to the difference between the refractive indices of background (air) and enamel. However, demineralization of enamel and dentin results in measurable changes of mineral density[27] and micropores are formed in the carious lesion due to partial dissolution of the individual mineral crystals.[28] It is highly probable that micro-interfaces between demineralized mineral crystals and water (or air) within the micropores cause higher reflectivity due to the local refractive index contrast, thus inducing increased brightness in the corresponding OCT image.[29] The magnitude of the scattering coefficient increases in proportion to demineralization,[30] thereby higher brightness was observed at the enamel surface of demineralization in OCT images.

It is noteworthy that a large number of previous OCT reports have focused on the time-domain PS-OCT systems. More, recently CP-SS-OCT reports[20,31] have also appeared in the literature, emphasizing the suitability of reflectivity parameters for the detection of demineralization, particularly in early enamel lesion. The PS-OCT (or CP-OCT) approach has also the advantage of decreasing the specular reflections from the surface of sample that may interfere with the signal analysis. On the other hand, conventional SS-OCT (without polarization sensitivity) has found great utility in nondestructive detection of gaps, cracks, and internal defects in the dental hard tissues and biomaterials.[17,32] It appears that a comprehensive comparison between the two OCT approaches with regard to their clinical applications in dentistry requires further investigations.
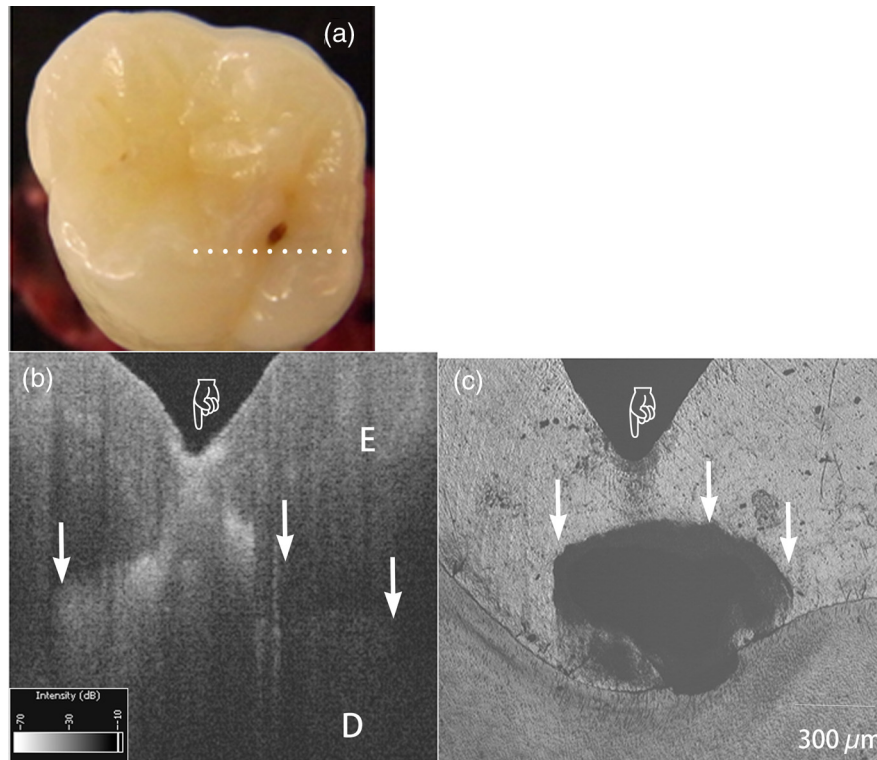
Fig. 3 Images obtained from occlusal surface with visual enamel demineralization. (a) In the photograph, brownish discoloration could be confirmed, but the presence of cavitation was not clear. (b) SS-OCT image obtained at line in (a). The presence of demineralization was recognized as a strong scattering signal (finger arrow). Reflecting SS-OCT signal was spread into the dentin and a slightly highlighted zone penetrated horizontally (arrow), indicating the presence of hidden caries. The score was three in SS-OCT. E, enamel and D, dentin. (c) CLSM observation clearly confirmed the presence of hidden caries. The hidden lesion with complete tissue loss (cavitation) was located at the inner enamel. Since the DEJ appeared roughened, the score of this area was three in CLSM.

Imaging depth of OCT is limited due to technical obstacles such as light attenuation through the tissue; however, cross-sectional images generated by SS-OCT provided useful information for the detection of dentin caries. Since the laser light of near-infrared at 1300-nm wavelength can penetrate with little attenuation through the sound enamel,[33] we could image the hidden caries underneath the occlusal enamel which visually appeared as sound or with slight demineralization.[34] If the hidden caries penetrates into dentin, axial propagation of the caries lesion creates numerous submicron spaces beneath the DEJ. Moreover, demineralization of dentin leaves a hydrated organic matrix (including collagen) that is known to scatter light.[30] In this manner, strong reflection from carious dentin results in bright appearance of dentin lesion in SS-OCT image.

In this study, SS-OCT was capable of imaging hidden caries *in vivo*. As shown in Fig. 5, SS-OCT provided a clear image of
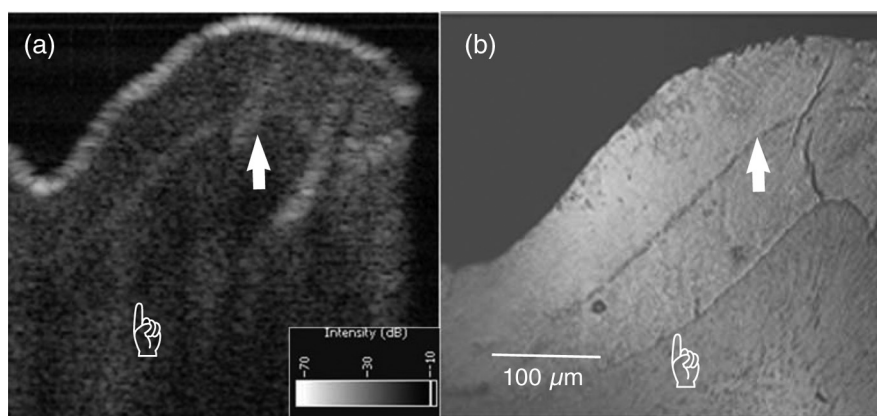
Fig. 4 Images obtained from intact enamel surface. (a) On the SS-OCT image, scattering line could be seen on the enamel layer (arrow). The DEJ was slightly visualized around finger point area. (b) In the CLSM observation, two lines (i.e., the neonatal line and the DEJ) could be clearly confirmed.

Table 2 Cut-off points, sensitivity, specificity, and *Az* value of ROC analysis in hidden caries of visual inspection and SS-OCT.

|	Cut-off	Sensitivity	Specificity	Az
Visual inspection	2 to 3	0.21	1.0	0.60
SS-OCT	2 to 3	0.88	0.92	0.90

hidden caries in real clinical situation, although merely yellow or brown discolorations of pit and fissure can be seen by visual examination. In this case, the cavity had been progressing without subjective symptom and it was difficult to outline the cavity clearly in the radiographical examination. It is noteworthy that SS-OCT laser beam undergoes significant attenuation in dentin; therefore, in the case of very deep penetration of caries into dentin, estimation of lesion extent may be challenging. Moreover, in the case of hidden caries with extensive loss of enamel and dentin creating a large hollow space within the tooth, the upper borders of the hollow space strongly scatter and attenuate light so that the axial extent of the lesion would be difficult to estimate. Nevertheless, in this case, the tooth is already in a stage where the surgical intervention is necessary to prevent further internal destruction.

Recently, International Caries Detection and Assessment System (ICDAS) was advocated for the diagnosis of caries lesion in visual inspection.[35] Since ICDAS-II has demonstrated acceptable accuracy and reproducibility,[36–38] the classification of the lesions for visual examination in this study was derived with modifications from ICDAS-II to simply and readily score caries progress. Although the results of our visual inspection showed quite high sensitivity for the detection of noncavitated early lesions, our visual investigations could not distinguish most of the advanced hidden caries from the less severe noncavitated lesions. Among dentin caries, six hidden caries cases were included in our *in vitro* study; the sensitivity of visual inspection for these cases was less than that of SS-OCT (Table 2). Since this result was consistent with our *in vivo* observations, SS-OCT appears to be advantageous over the visual inspection for the detection of hidden caries. One of the reasons for the lower sensitivity of visual inspection is that the occlusal fissure of the primary teeth extend deeply into the enamel, and the enamel below the fissure is extremely thin.[39] These deep, narrow I-shaped fissures may also have a number of different branches extending toward or into the underlying dentin.[1] Consequently, visual distinction of these deep fissures from caries is clinically difficult. SS-OCT can be used as a valid detecting tool to assist visual assessment by ICDAS in case if hidden lesion was suspected at the occlusal fissure.

It is well documented that sealants are effective for preventing caries not only permanent teeth but primary teeth.[40] To date, sealing fissures with an adhesive material has been considered as an appropriate treatment option for arresting the superficial caries.[41] On the other hand, surgical intervention is thought to be necessary to remove the bacterial infected zone where caries has progressed into dentin and suppression of cariogenic bacteria is impossible. The cross-sectional view of hidden lesion in SS-OCT appears to provide strong and constructive information in the decision-making process over the clinical treatment approach.

In the current study, SS-OCT could clearly observe the neonatal line (Fig. 4), which is a histologic landmark in primary tooth enamel corresponding to the event of birth.[42,43] In SS-OCT image, the neonatal line appears as a bright borderline similar to DEJ. However, considering the enamel thickness and that the optical characteristics of the enamel and dentin differ owing to the structural and compositional factors,[27] the neonatal line and DEJ can be distinguished from each other. Meanwhile,
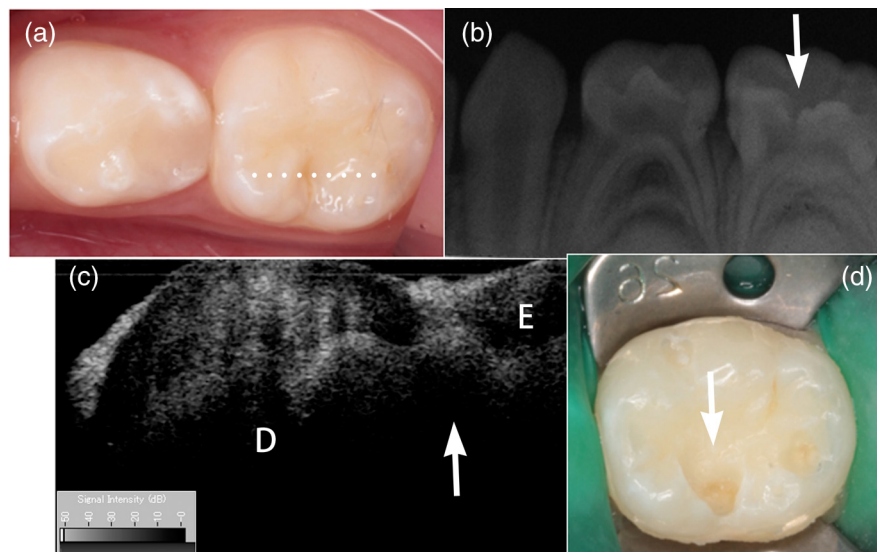
Fig. 5 Images obtained from lower second primary molar (5 years, male). (a) Occlusal view before the surgical treatment. An underlying brown spot was observed at the second primary molar (white dotted line). (b) On dental X-ray image, discontinuity of enamel layer was observed on the fissure (arrow). (c) On the SS-OCT image, the presence of caries was clearly detected as a highlighted zone (arrow). Beneath the deepest part of the fissure, a strong but narrow reflection from the enamel layer was observed. The brighter zone with higher scattering was spread along the DEJ and into dentin. (d) Occlusal view after the caries removal of the second primary molar using low speed rotary instruments. A dentin cavity was prepared after the caries removal (arrow).

in some SS-OCT images DEJ could not be visualized clearly, probably due to thick overlying enamel and the scanning angle relative to the DEJ orientation. It has been shown that the orientation of OCT beam in relation to the inclination of the structure can affect the signal intensity, i.e., a steep slope at the enamel surface may not appear as bright as a less steep surface.[32]

A comparison of the results between the present study and a previous one suggested that a higher sensitivity (0.75) was found for the detection of dentin caries in primary teeth compared with the permanent teeth (0.60),[16] indicating that using SS-OCT device, dentin caries in primary teeth is more accurately detected and quantified than in permanent teeth. Thickness of occlusal enamel in primary molar is approximately 2 mm, whereas in the permanent enamel it is 3 mm.[44] Thinner enamel layer in primary teeth may cause less attenuation of laser scanning light of SS-OCT resulting in the higher sensitivity for the detection of dentin caries.

The CLSM observation in the current *in vitro* research was performed as a standard to confirm the presence and extent of caries lesions at each investigation site. When CLSM was used, the presence of demineralized area could be observed as a dark structure. The microscopic method has been used in several fields of dental research including cross-sectional observation of caries and biomaterial–tooth interfaces.[16,29,32] On the other hand, transversal microradiography (TMR) is regarded as the gold standard to determine mineral loss and depth of enamel caries lesions but requires preparation of thin sections.[45] High-resolution conventional light-microscopy is another alternative for such cross-sectional observation; however, the advantage of CLSM would be the ability to produce a focused image of a rather rough surface at higher magnifications because of the confocal function. CLSM is advantageous over electron microscopy methods regarding preparation and immediate observation. It was reported that CLSM and TMR data showed a good correlation to evaluate the enamel demineralization depth.[46] In addition, it was possible to verify the investigation site at various stages during trimming and further trim specimen, if necessary, to reach the desired cross section that was imaged by SS-OCT.

In this study, the depth range of the SS-OCT imaging was approximately 2.0 mm in primary teeth. An extended depth range seems to be required to image the entire hidden caries if it is deep and close to the pulp. Nevertheless, the complex pattern of light-scattering in dentin which is affected by the composition and structural orientation of this natural substrate imposes some limitations on deep imaging through this tissue using the current OCT technology. Therefore, further technical development and innovation on interferometric imaging are needed to enable evaluation of advanced hidden lesions.

One of the main advantages of SS-OCT imaging compared with radiography is the ability to visualize the internal structure without the use of ionizing radiation. Children are more sensitive to radiation than adults because the number of dividing cells promoting DNA mutagenesis is higher and they have more time to express any radiation-induced effects, such as cancer.[47] In addition, radiographs are unable to diagnose early enamel caries lesions reliably. OCT systems equipped with hand-held probes suitable for intraoral imaging have become available.[20,33] Although these systems are not widely commercialized as dental OCT systems yet, the availability and improvements of these hand-held probes would support the adoption of the technology for clinical use. Therefore, SS-OCT can be safely performed for as many times as required in real time, as an alternative to the conventional radiography used for the detecting tool of occlusal caries, especially in younger children.

5 Conclusions

Within the limitation of this *in vitro* part of study, the demineralization induced by caries process could be clearly discriminated as a highlighted area due to scattering of light, and the results correlated well with the CLSM. Regarding the detection of dentin caries where the occlusal enamel appears clinically sound or only minimally demineralized, the sensitivity of SS-OCT results was superior to that of visual inspection. It is also suggested that SS-OCT could image the cross-sectional view of occlusal caries lesions in real clinical situations. SS-OCT appears to be a potential detecting method for assessment of hidden caries on primary teeth.

References

1. M. Rohr, O. F. Makinson, and M. F. Burrow, "Pits and fissures: morphology," *ASDC J. Dent. Child.* **58**(2), 97–103 (1991).
2. M. Demirci, S. Tuncer, and A. A. Yuceokur, "Prevalence of caries on individual tooth surfaces and its distribution by age and gender in university clinic patients," *Eur. J. Dent.* **4**(3), 270–279 (2010).
3. P. R. Wilson and A. D. Beynon, "Mineralization differences between human deciduous and permanent enamel measured by quantitative microradiography," *Arch. Oral. Biol.* **34**(2), 85–88 (1989).
4. K. L. Weerheijm, W. E. van Amerongen, and C. O. Eqqink, "The clinical diagnosis of occlusal caries: a problem," *ASDC J. Dent. Child.* **56**(3), 196–200 (1989).
5. K. L. Weerheijm, R. J. Gruythuysen, and W. E. van Amerongen, "Prevalence of hidden caries," *ASDC J. Dent. Child.* **59**(6), 408–412 (1992).
6. E. A. Kidd, M. N. Naylor, and R. F. Wilson, "Prevalence of clinically undetected and untreated molar occlusal dentine caries in adolescents on the Isle of Wight," *Caries Res.* **26**(5), 397–401 (1992).
7. B. Newman et al., "Clinical detection of caries in the primary dentition with and without bitewing radiography," *Aust. Dent. J.* **54**(1), 23–30 (2009).
8. S. J. Moss, H. Addelston, and E. D. Goldsmith, "Histologic study of pulpal floor of deciduous molars," *J. Am. Dent. Assoc.* **70**(2), 372–379 (1965).
9. J. A. Rayner and J. C. Southam, "Pulp changes in deciduous teeth associated with deep carious dentine," *J. Dent.* **7**(1), 39–42 (1979).
10. D. Kassa et al., "Histological comparison of pulpal inflammation in primary teeth with occlusal or proximal caries," *Int. J. Paediatr. Dent.* **19**(1), 26–33 (2009).
11. Y. Zadik and R. Bechor, "Hidden occlusal caries: challenge for the dentist," *N. Y. State Dent. J.* **74**(4), 46–50 (2008).
12. D. Huang et al., "Optical coherence tomography," *Science* **254**(5035), 1178–1181 (1991).
13. F. I. Feldchtein et al., "In vivo OCT imaging of hard and soft tissue of the oral cavity," *Opt. Express* **3**(6), 239–250 (1998).
14. L. L. Otis et al., "Optical coherence tomography: a new imaging technology for dentistry," *J. Am. Dent. Assoc.* **131**(4), 511–514 (2000).
15. M. A. Choma et al., "Sensitivity advantage of swept source and Fourier domain optical coherence tomography," *Opt. Express* **11**(18), 2183–2189 (2003).
16. Y. Shimada et al., "Validation of swept-source optical coherence tomography (SS-OCT) for the diagnosis of occlusal caries," *J. Dent.* **38**(8), 655–665 (2010).

17. Y. Nakajima et al., "Noninvasive cross-sectional imaging of incomplete crown fractures (cracks) using swept-source optical coherence tomography," *Int. Endod. J.* **45**(10), 933–941 (2012).
18. T. Yoshioka et al., "detection of root surface fractures with swept-source optical coherence tomography (SS-OCT)," *Photomed. Laser Surg.* **31**(1), 23–27 (2013).
19. A. M. A. Maia et al., "Characterization of enamel in primary teeth by optical coherence tomography for assessment of dental caries," *Int. J. Paediatr. Dent.* **20**(2), 158–164 (2010).
20. P. Lenton et al., "Imaging in vivo secondary caries and ex vivo dental biofilms using cross-polarization optical coherence tomography," *Dent. Mater.* **28**(7), 792–800 (2012).
21. Y. Shimada et al., "Noninvasive cross-sectional imaging of proximal caries using swept-source optical coherence tomography (SS-OCT) in vivo," *J. Biophotonics* 1–8 (2013).
22. Z. V. Hilsen and R. S. Jones, "Comparing potential early caries assessment methods for teledentistry," *BMC Oral Health* **13**(16) (2013).
23. D. C. Attrill and P. F. Ashley, "Occlusal caries detection in primary teeth: a comparison of DIAGNOdent with conventional methods," *Br. Dent. J.* **190**(8), 440–443 (2001).
24. J. F. Souza et al., "Traditional and novel methods for occlusal caries detection: performance on primary teeth," *Lasers Med. Sci.* **28**(1), 287–295 (2013).
25. P. Rechmann et al., "Performance of laser fluorescence devices and visual examination for the detection of occlusal caries in permanent molars," *J. Biomed. Opt.* **17**(3), 036006 (2012).
26. D. Fried et al., "Imaging caries lesions and lesion progression with polarization sensitive optical coherence tomography," *J. Biomed. Opt.* **7**(4), 618–627 (2002).
27. I. Hariri et al., "Estimation of the enamel and dentin mineral content from the refractive index," *Caries Res.* **47**(1), 18–26 (2013).
28. C. L. Darling, G. D. Huynh, and D. Fried, "Light scattering properties of natural and artificially demineralized dental enamel at 1310 nm," *J. Biomed. Opt.* **11**(3), 034023 (2006).
29. H. Nakagawa et al., "Validation of swept source optical coherence tomography (SS-OCT) for the diagnosis of smooth surface caries in vitro," *J. Dent.* **41**(1), 80–89 (2013).
30. Y. Natsume et al., "Estimation of lesion progress in artificial root caries by swept source optical coherence tomography in comparison to transverse microradiography," *J. Biomed. Opt.* **16**(7), 071408 (2011).
31. K. H. Chan et al., "Use of 2D images of depth and integrated reflectivity to represent the severity of demineralization in cross-polarization optical coherence tomography," *J. Biophotonics* (in press) (2013).
32. B. Bista et al., "Non-destructive assessment of current one-step self-etch dental adhesives using optical coherence tomography," *J. Biomed. Opt.* **18**(7), 76020 (2013).
33. M. M. Mandurah et al., "Monitoring remineralization of enamel subsurface lesions by optical coherence tomography," *J. Biomed. Opt.* **18**(4), 046006 (2013).
34. S. K. Manesh, C. L. Darling, and D. Fried, "Polarization-sensitive optical coherence tomography for the nondestructive assessment of the remineralization of dentin," *J. Biomed. Opt.* **14**(4), 044002 (2009).
35. N. Pitts, "ICDAS"—an international system for caries detection and assessment being developed to facilitate caries epidemiology, research and appropriate clinical management," *Community Dent. Health* **21**(3), 193–198 (2004).
36. R. Matos et al., "Clinical performance of two fluorescence-based methods in detecting occlusal caries lesions in primary teeth," *Caries Res.* **45**(3), 294–302 (2011).
37. T. F. Novaes et al., "Performance of fluorescence-based and conventional methods of occlusal caries detection in primary molars—an in vitro study," *Int. J. Paediatr. Dent.* **22**(6), 459–466 (2012).
38. L. Shoaib et al., "Validity and reproducibility of ICDAS II in primary teeth," *Caries Res.* **43**(6), 442–448 (2009).
39. K. V. Mortimer, "The relationship of deciduous enamel structure to dental disease," *Caries Res.* **4**(3), 206–223 (1970).
40. S. O. Griffin et al., "The effectiveness of sealants in managing caries lesions," *J. Dent. Res.* **87**(2), 169–174 (2008).
41. M. A. Hevinga et al., "Can caries fissures be sealed as adequately as sound fissures?," *J. Dent. Res.* **87**(5), 495–498 (2008).
42. I. Eli, H. Sarnat, and E. Talmi, "Effect of the birth process on the neonatal line in primary tooth enamel," *Pediatr. Dent.* **11**(3), 220–223 (1989).
43. N. Sabel et al., "Neonatal lines in the enamel of primary teeth—a morphological and scanning electron microscopic investigation," *Arch. Oral. Biol.* **53**(10), 954–963 (2008).
44. A. Lucchese and E. Storti, "Morphological characteristics of primary enamel surfaces versus permanent enamel surfaces: SEM digital analysis," *Eur. J. Paediatr. Dent.* **12**(3), 179–183 (2011).
45. M.K. Pugach et al., "Dentin caries zones: mineral, structure, and properties," *J. Dent. Res.* **88**(1), 71–76 (2009).
46. H. Meyer-Lueckel and S. Paris, "Progression of artificial enamel caries lesions after infiltration with experimental light curing resin," *Caries Res.* **42**(2), 117–124 (2008).
47. C. Theodorakou et al., "Estimation of pediatric organ and effective doses from dental cone beam CT using anthropomorphic phantoms," *Br. J. Radiol.* **85**(1010), 153–160 (2012).

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