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Abstract. The aim of this study was to evaluate the signal intensity and signal attenuation of swept source optical coherence tomography (SS-OCT) for dental caries in relation to the variation of mineral density. SS-OCT observation was performed on the enamel and dentin artificial demineralization and on natural caries. The artificial caries model on enamel and dentin surfaces was created using *Streptococcus mutans* biofilms incubated in an oral biofilm reactor. The lesions were centrally cross sectioned and SS-OCT scans were obtained in two directions to construct a three-dimensional data set, from the lesion surface (sagittal scan) and parallel to the lesion surface (horizontal scan). The integrated signal up to 200 μm in depth (IS200) and the attenuation coefficient (μ) of the enamel and dentin lesions were calculated from the SS-OCT signal in horizontal scans at five locations of lesion depth. The values were compared with the mineral density obtained from transverse microradiography. Both enamel and dentin demineralization showed significantly higher IS200 and μ than the sound tooth substrate from the sagittal scan. Enamel demineralization showed significantly higher IS200 than sound enamel, even with low levels of demineralization. In demineralized dentin, the μ from the horizontal scan consistently trended downward compared to the sound dentin. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JMI.3.3.035507]

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1 Introduction

Dental caries is one of the most ubiquitous diseases and is caused by the metabolic activities of microorganisms that colonize the oral cavity.¹ Dental caries is the demineralization of inorganic minerals of teeth by the acid produced by oral bacteria.² *Streptococcus mutans* is one of the oral bacteria but the main cause of dental caries.³ Since *S. mutans* can directly adhere to the tooth's hydroxyapatite (HA) matrix,⁴ the pH of the tooth surface is easily reduced to a level below 5.5, which is thought to be the critical pH of HA demineralization under normal conditions.⁵

The diagnosis of carious lesions in early stage is an important aspect of routine dental practice, because the initial enamel lesion can be arrested and may have the potential for remineralization by nonsurgical intervention methods such as fluoride agents (toothpaste, mouth rinse, gel, varnish, or other solutions) or resin infiltration.^{6–10} However, detecting dental caries lesions at an early stage before the need for surgical intervention remains a major challenge. Implementation of minimal intervention strategies requires a powerful diagnostic modality. Traditionally, the

extent of carious lesions has been assessed by clinical inspection to evaluate physical features such as tooth color and surface morphology as well as by radiography.^{11,12} Dental radiographs typically show low sensitivity, while the true extent of caries lesions is usually underestimated when relying solely on radiographs.^{11,12}

Optical coherence tomography (OCT) is a noninvasive diagnostic method that allows the creation of cross sectional images of internal biological structures.¹³ OCT was developed on the concept of low-coherence interferometry where the light is projected over a sample, and the backscattered signal intensity from the scattering medium reveals depth resolved information about scattering and reflection of the light in the sample. A cross sectional image (B scan) is generated by performing multiple axial measurement of echo time delay (A scan) and scanning the incident optical beam transversely. OCT images can differentiate the optical properties of various tissues, including the effects of optical absorption and scattering.^{14–16}

Swept-source OCT (SS-OCT) is a type of OCT in which the light source is a tunable laser that sweeps near-infrared wavelength light with millisecond-scan delays at kilohertz rates to achieve near real-time video-rate imaging.¹⁷ Improved imaging

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resolution of SS-OCT enables application of caries diagnosis that shows high sensitivity and specificity for the detection of enamel caries.¹⁸ Furthermore, advanced imaging depth of SS-OCT permits the detection of dentin caries in clinical situations.¹⁹ Both the sensitivity and specificity of SS-OCT for the diagnosis of proximal caries were higher than the dental radiographs up to the depth of superficial dentin caries.¹⁹ Three-dimensional (3-D) volumetric data sets can easily be obtained in a short time due to the enhanced scanning speed in SS-OCT. Since the signal intensity and attenuation patterns of SS-OCT images are influenced by the presence of caries, attempts were made to utilize the signal intensity and attenuation coefficient as quantitative parameters for the detection of carious.^{20–24} However, limited information is available on the potential use of OCT signals. It was suggested that demineralized enamel resulted in a quick and exponential decline of backscatter signal with depth, due to the increased porosity of the tissue. However, the reflection pattern of OCT signal in dentin is more complicated owing to the nature of tissue and the role of dentinal tubules. Signal attenuation through the sound dentin is higher than that of the sound enamel, as the dentin contains over 50 vol% of organic structure and fluid, which scatter and absorb the light.

In this study, we exposed specimens of enamel and dentin to biofilms of *S. mutans* in a caries demineralization model system and examined the demineralized surfaces using SS-OCT. Signal intensity and attenuation of the SS-OCT images obtained from artificial caries models and natural caries were evaluated and compared with the results from sound tooth structure. Two directions of SS-OCT scan were performed on the substrate along the direction of demineralization and parallel to the demineralization in order to evaluate the influence of demineralization level on the SS-OCT signal.

2 Materials and Methods

Forty extracted human molar or premolar teeth (20 intact teeth, 10 with enamel caries, and 10 with dentin caries) were preserved in 4°C water until their use in this study. The use of these extracted teeth was in accordance with the policies of the ethics committee of Tokyo Medical and Dental University (approval number 725).

Twenty sections each of enamel and dentin were created from twenty intact teeth and then cut into 5 mm × 5 mm × 3 mm pieces. These pieces were divided into two groups of ten specimens each (Fig. 1). The upper surface of each specimen was ground flat using a #800 grit abrasive paper under running water. Ten enamel and 10 dentin slabs were selected and subjected to bacterial demineralization using *S. mutans* *in vitro*. The remaining enamel and dentin slabs were immersed in phosphate buffered saline (PBS) (pH = 7.2 to 7.3) for seven days as control groups. The teeth with natural caries in the enamel or dentin were also immersed in PBS for seven days, then sectioned through the center of each lesion and ground flat using a #800 grit abrasive paper.

2.1 Oral Biofilm Reactor and Bacterial Demineralization

An oral biofilm reactor (OBR) was used in the application of *S. mutans* to create an enamel and dentin demineralization model, as previously reported (Fig. 2).^{25,26} In brief, *S. mutans* MT8148 was cultured in brain heart infusion (BHI) (Becton Dickinson, Sparks, Maryland) broth for 16 h. After the bacteria were washed three times with PBS, a suspension of *S. mutans* in PBS at an optical density 500 nm (OD₅₀₀) = 2 containing ~2 × 10⁷ colony-forming units/ml was prepared and stored at 4°C

Fig. 1 Schematic view of specimen preparation for the experiment. Forty extracted human teeth (20 intact teeth, 10 enamel caries, and 10 dentin caries) were used in this study. Ten enamel and 10 dentin slabs (5 mm × 5 mm × 3 mm) were prepared and subjected to bacterial demineralization using *S. mutans*. The remaining slabs were immersed in PBS and used as controls. Teeth with natural enamel caries and dentin caries were also sectioned into 5 mm × 5 mm × 3 mm. All specimens were observed under SS-OCT and TMR.

Fig. 2 Biofilm formation using OBR. Samples were placed on a Teflon holder around a flat bulb pH electrode of OBR using the red utility wax. The chamber encircled by a water jacket was sealed with another silicon plug fitted with stainless steel tubes so that the chamber itself served as an incubator with a 37°C inner temperature. The other ends of the stainless steel tubes were connected to silicon tubes passing through peristaltic pumps that were regulated by a computer-operated controller. The tubes were used to collect the *S. mutans* suspension, HI, and PBS from the prepared stock. All of these liquids were pumped into the chambers at a rate of 6 ml/h tube so that the liquids could continuously drop onto the center of the specimen holder. The chambers were simultaneously operated, and pH on the flat bulb electrode was continuously recorded.

with gentle stirring to maintain a high density of *S. mutans*. A solution of heart infusion (HI) (Becton Dickinson) broth with 1% sucrose was used as a nutrient broth.

The OBR chamber contained a warm water jacket to maintain a constant interior temperature and a liquid dome located inside the chamber prevented direct contact of the biofilm with available O_2 . To monitor the pH beneath the biofilm continuously, a flat-bulb pH electrode attached to a recorder was used. The reduction in the pH was similar in all the experiments reported here, with the initial pH of 7.35 beginning to decrease within 2 h and the measured reduction being below pH 4.0 within 20 h.

Cariogenic biofilms were grown on specimens *in vitro* inside the two identical, water jacket-encircled OBR chambers. Ten enamel and 10 dentin specimens were prepared from intact teeth, followed by ultrasonic cleaning in 0.5 M NaOH for 20 min and 99% ethanol rinse for 10 min to remove any micro-organisms. The specimens were then placed on a Teflon holder around a flat-bulb pH electrode within OBR using red utility wax (GC, Tokyo, Japan) in such a way that only the experimental surface remained open for biofilm attachment. The open surface of each specimen was kept horizontal at the level of the bulb surface. The Teflon holders bearing the specimens were set in place through the bottom opening of the chamber using a silicon plug. Pooled sterile saliva was then poured on the specimens and the pH electrode from above and then incubated with the specimens to obtain a salivary pellicle coating.

The water jacket encircling each chamber created an incubator with a 37°C inner temperature. The *S. mutans* suspension, HI-sucrose, and PBS were pumped into the chambers for 20 h at 6 ml/h/tube so that each solution dropped continuously onto the center of the specimen holder. Both chambers were

simultaneously operated, and the pH on the flat-bulb electrode was recorded continuously.

After 20 h, each specimen with an artificial biofilm was transferred to a well in a 24-well tissue culture plate (Corning Inc., New York, New York) and incubated at 37°C in HI-sucrose medium for an additional 7 days, with the media being exchanged on alternate days. After the end of 7-day incubation, the biofilm from each specimen was removed using 0.5-M NaOH solution by shaking on a water bath shaker operating at 10 Hz, for 10 min. The procedure was performed twice at 1-min intervals for OBR enamel and OBR dentin. The demineralized tooth samples were trimmed using a rotary diamond stone and #800 grit SiC abrasive paper to expose a cross sectional view at the center of the demineralized zone.

2.2 Swept Source Optical Coherence Tomography Observation

The SS-OCT system (Yoshida Dental MFG, Tokyo, Japan) used in this experiment is a frequency domain OCT technique that measures the magnitude and time delay of reflected light in order to construct a depth profile. The wavelength ranges from 1240 to 1380 nm, with a central wavelength of 1310 nm at a 50-kHz sweep rate. A 3-D data set is obtained at optical resolution in air under 11 μm in depth and 30 μm in width and length. Two directions of SS-OCT scan were performed to get the 3-D data set on the demineralized enamel and dentin induced by the *in vitro* cariogenic biofilms inside OBR (named as: OBR enamel and OBR dentin, respectively), and on the natural caries (Fig. 3).

One of the scans was performed from the lesion surface along the direction of demineralization (sagittal scan). The two-dimensional (2-D) images were chosen from the center of the OBR demineralization and natural caries. This scanning direction was on the assumption of a clinical situation for caries diagnosis (Fig. 3).

The other scanning direction was a horizontal view parallel to the demineralization direction (horizontal scan). Five 2-D scans were chosen from the 3-D data set parallel to the lesion surface at 75- μm intervals from the subsurface (0 μm) up to

Fig. 3 Schematic illustration for the direction of SS-OCT scanning. Two directions of 3-D scanning were performed on the demineralized samples. One of the scans was performed from the lesion surface along the direction of demineralization (sagittal scan). The 2-D images were chosen from the center of the lesion. The other scanning direction was a horizontal view parallel to the demineralization direction (horizontal scan). Five 2-D images at 75- μm intervals up to 300 μm in depth were selected; 0, 75, 150, 225, and 300 μm lesion depth were obtained.

300 μm in depth. As a result, five 2-D images at 0, 75-, 150-, 225-, and 300- μm lesion depth were obtained. Since the degree of demineralization is almost homogeneous within these 2-D planes, SS-OCT signals were evaluated in relation to the demineralization level obtained from transversal microradiography (TMR) study (Figs. 3 and 4).

From each 2-D scan, 10 A scan signals were chosen and signal intensity in dB units was integrated from the surface through the depth of 200 μm (integrated signal up to 200- μm depth, IS200). Because of the discrepancy of mineral density and mineral distribution between the sagittal scan and horizontal scan, IS200 from the sagittal scan was named as SIS200, whereas the horizontal scan was HIS200. Since the surface reflection from the sample was not intense enough to disturb the further analysis in this SS-OCT, the signal from the surface was also included in this experiment (Fig. 4).

The attenuation coefficient (μ) of SS-OCT signal for the enamel and dentin lesions were also calculated from the A scan signal based on the exponential decay of irradiance from the specimen surface using an equation derived from the Beer-Lambert law in Eq. (1), as reported previously.^{23,24}

$$I(z) \propto e^{-2\mu z}, \quad (1)$$

where I is the reflectivity signal intensity in (dB) and z is the depth variable in mm. μ was calculated using linear least-squares regression to fit the natural log of the average OCT profiles obtained from the region of interest in Eq. (2).

$$\mu \propto -\frac{\ln I(z)}{2z}, \quad (2)$$

where the μ from sagittal scan was named $S\mu$ and μ from horizontal scan was $H\mu$ in this study.

2.3 Transversal Microradiography Observation

After SS-OCT images were captured, all biofilm demineralization and natural caries specimens were processed for TMR to measure mineral density as previously reported (Fig. 1).^{21,22} The specimens were embedded in an epoxy resin (Epoxiure resin, Buehler). After 24 h, they were cut into 200- to 250- μm thick sections, using a low-speed diamond saw (Isomet, Buehler, Lake Bluff, Illinois).

TMR images were captured for each slice using an x-ray generator (Softex CMR-2; Softex Co., Ltd., Japan) set at 20 kV and 2.5 mA for 8 min with a Ni filter. The distance between the x-ray tube and the specimen was 15 cm. The TMR images, together with 15 aluminum step wedges of 15- μm thickness were captured on x-ray glass plate film (High Precision Photo Plate PXHW, Konica Minolta Photo, Tokyo, Japan) and then scanned as 8-bit digital images using a CCD camera (DP70, Olympus, Tokyo, Japan) attached to a microscope (BX41, Olympus). Mean mineral profiles (mineral density versus depth) were created using the Image-J software and a custom Visual Basic application for Microsoft Excel. Demineralization was determined to be present when the mineral density was 5% less than that recorded for the sound dentin in a 500 $\mu\text{m} \times 5000 \mu\text{m}$. The mineral density (vol%) was calculated using the calibration curve based on sound enamel having a mineral density of 87 vol% and dentin containing a mineral density of 48 vol%. The HIS200 and $H\mu$ values obtained from horizontal scans for the imaging depth at 0, 75, 150, 225, and 300 μm were linked with the TMR results and were compared with the mineral densities.

Fig. 4 (a) SS-OCT horizontal scanning and calculation for HIS200. 3-D image construction of the lesion was performed on the demineralized enamel and dentin slabs created in an OBR and on natural caries. (b) Five 2-D images were chosen from the 3-D data set collected at 0-, 75-, 150-, 225-, and 300- μm lesion depth. (c) Ten A scan signals were selected from the 2-D images and (d) the signal intensities were integrated through the 200- μm depth from the profile (HIS200).

2.4 Statistical Analyses

HIS200 and $H\mu$ values for horizontal SS-OCT scans from the depth of 0, 75, 150, 225, and 300 μm were compared with TMR mineral densities, and polynomial approximation curves were determined using an iterative method based on least-squares.

The HIS200 and $H\mu$ of demineralized enamel and dentin collected at 75- μm intervals were compared with the values obtained from the sagittal scan and sound tooth structure (Student *t*-test). The variance of HIS200 and $H\mu$ values within the lesion was also analyzed using the ANOVA test. Significance levels were defined as $p = 0.05$.

3 Results

Representative SS-OCT images obtained from OBR demineralization and natural caries are shown in Fig. 5. In the demineralized lesions, the backscattered signal increases and the demineralized region appears bright on the gray scale image. For the sagittal scan, the highlighted zone was observed to the surface zone where the demineralization lesion was located, of which brightness was vividly decreased toward the intact zone. Nevertheless, in horizontal scans the demineralized tooth substrate could be observed in depth in all scans even at the superficial scans with strong demineralization.

The integrated signal (SIS200 and HIS200) and attenuation coefficient ($S\mu$ and $H\mu$) values obtained from two scanning directions are shown in Fig. 6. For the sagittal scan, both OBR demineralization and natural caries showed significant increase in SIS200 and $S\mu$ over the sound tooth structure (Student *t*-test, $p < 0.05$). For the horizontal scan, HIS200 and $H\mu$ values at various depths of 0, 75, 150, 225, and 300 μm showed similar values within each group (one-way ANOVA, $p > 0.05$). Generally, HIS200 and $H\mu$ values for horizontal scans were lower than the values for the sagittal scan

except for the caries enamel, where HIS200 and SIS200 appeared to be similar. When the values are compared with sound structure, HIS200 of OBR and carious enamel were significantly higher than the sound enamel in all the scanning depths. In dentin, a significant increase of HIS200 over the sound structure was detected only at the scanning depth up to 150 μm of OBR demineralization (Student *t*-test, $p < 0.05$). In contrast, $H\mu$ values exhibited a different trend between the demineralized enamel and dentin. For enamel, the $H\mu$ values were increased compared with the sound enamel, where OBR demineralization showed a significant increase in all the scanning depths. However, the $H\mu$ values in dentin exhibited a decreasing trend for both OBR demineralization and natural caries. Significant decrease was detected in OBR dentin at a scanning depth of 75 μm (Student *t*-test, $p < 0.05$).

Representative TMR images of each group together with their mineral density profiles at different depths are shown in Fig. 7. Demineralized zones were clearly observed as dark areas in OBR demineralization and natural caries due to the mineral loss. The mean values of lesion depth $\pm$ standard deviations for OBR enamel, OBR dentin, carious enamel, and carious dentin as measured from TMR profiles were $169.1 \pm 15.9 \mu\text{m}$, $215.1 \pm 34.8 \mu\text{m}$, $325.6 \pm 148.9 \mu\text{m}$ and $347.8 \pm 79.9 \mu\text{m}$, respectively.

Distribution of HIS200 and $H\mu$ values in relation to the mineral density (vol %) from the TMR profile, as well as the polynomial approximation curves are shown in Fig. 8. Approximation curves of HIS200 for both OBR demineralization and natural caries were higher than the values of sound enamel and dentin. Except at the lowest mineral density zone (12% mineral density) and the highest mineral density zone (over 80% mineral density) for natural caries, most part of approximation curves of $H\mu$ values for enamel demineralization was higher than the sound enamel value. On the other hand,

Fig. 5 Representative 2-D images derived from sagittal scan and horizontal scans collected at 0-, 75-, 150-, 225-, and 300- μm lesion depth. The demineralized regions appear bright on the gray scale SS-OCT images (in sagittal scan, solid white stars). Horizontal scans display deeper lesion body than the sagittal scan. The brightness at 1-mm depth (open white stars) is higher in horizontal scans especially in OBR enamel.

Fig. 6 Signal intensity up to 200- μm depth (IS200) and signal attenuation coefficient obtained from sagittal scan (SIS200 and S_μ) and horizontal scan (HIS200 and H_μ). (a) Significant difference with sound tooth (Student *t*-test, $p < 0.05$). (b) Significant difference for horizontal scan values with the sagittal scan (Student *t*-test, $p < 0.05$).

H_μ for demineralized dentin from OBR demineralization and natural caries was lower than that for sound dentin.

4 Discussion

Demineralization of dental caries increases in porosity as a result of mineral loss within the lesion body. Seven days of demineralization by cariogenic biofilm could create artificial lesions with mean depths of 169.1 μm in enamel and 215.1 μm in dentin. For the natural caries, TMR mineral density analyses showed a mean enamel lesion depth of 325.6 μm , and mean dentin lesion depth of 347.8 μm (Fig. 7). The lesion depths of natural caries were significantly deeper than those of the bacterial demineralization, with deeper demineralization of dentin than enamel. The microscopic interfaces within the pores cause higher reflectivity, resulting in increased brightness in SS-OCT images.^{14,21,27}

In this study, two directions of SS-OCT scans to the enamel and dentin lesions were performed in order to evaluate the SS-OCT signal for the variation of mineral loss (Figs. 3 and 4). From the horizontal scans, mineral density at five locations of lesion depth could be determined by the cross-check against the results of the TMR profile; in this manner, the OCT scanning beam would be projected on the tissue in the same direction as the TMR x-ray beam. For the analysis of OCT signal intensity, the reflectivity intensities up to 200 μm in depth were integrated, and the integrated values from the sagittal scan and horizontal scan were defined as SIS200 and HIS200, respectively (Fig. 4).

The results obtained from sagittal scans were well correlated with previous studies.^{15,28–31} The SIS200 and S_μ values were more significantly increased for the OBR demineralization

and natural caries than the intact tooth structure (Fig. 6). Consequently, it is highly probable that signal intensity and signal attenuation coefficient from the sagittal scan can be utilized as objective parameters for the detection of enamel and dentin demineralization.^{23,24} This result is relevant in clinical situations, where an occlusal or facial surface can be sagittally imaged by SS-OCT.

On the other hand, the current work appears to be the first study to investigate OCT signal intensity of demineralized and carious dental tissue in horizontal scans. Interestingly, horizontal scans of SS-OCT could demonstrate the demineralized lesion body deeper than the sagittal scans (Fig. 5). Additionally, the results of the signal intensity and attenuation coefficient from the horizontal scans were lower than the values from sagittal scans (Fig. 6). Although the values were lower than the sagittal scans, horizontal scans on the OBR enamel and carious enamel showed significantly higher HIS200 values over the sound enamel (Fig. 6). Increased HIS200 values due to the demineralization were almost at the same level even with lower demineralization; the HIS200 value for natural caries was almost 1200, even at 80% mineral density (Fig. 8). This finding is probably the result of the number of pores within the demineralized enamel remaining fairly constant at the higher mineral densities, creating a similar intensity of light scattering.^{16,20} The increased HIS200 at the enamel with low mineral loss appears to agree with a previous report of excellent SS-OCT detectability of early enamel demineralization.³² It is well evidenced that because of the formation of numerous micro porosity created by mineral loss,¹⁴ the scattering coefficient of demineralized enamel shows a 2–3 fold increase over that of sound enamel.¹⁶ Although the size of the demineralized pores was not measured

Fig. 7 Representative TMR images and the associated mineral density profile. Demineralized zones were clearly observed as dark areas on OBR demineralization and natural caries specimens.

in this experiment, Darling et al.³⁰ demonstrated that the pores in demineralized lesions highly scattered light suggesting Mie-like scatters. Since Mie scattering is the phenomenon where the size of the scattering particles is comparable to the wavelength of the light, the size of the pores or demineralized enamel crystals appears roughly close to the SS-OCT wavelength 1310 nm or more.

When $H\mu$ was calculated at five different depths, [0 (lesion surface), 75, 150, 225 and 300 μm], a significant increase in $H\mu$ in OBR enamel was observed over the sound enamel (Fig. 6). In contrast, $H\mu$ for enamel from natural caries was not significantly different from that for sound enamel. Since demineralization with *S. mutans* occurs in the absence of remineralization, it is highly probable that OBR demineralization caused by a cariogenic biofilm is more aggressive than natural lesions, resulting in a significant increase in HIS200 as well as $H\mu$ for OBR lesions.

In dentin, OBR demineralization and natural caries rendered the $H\mu$ value lower but not significantly lower than that for sound dentin, with the exception of OBR demineralization at a depth of 75 μm (Figs. 6 and 8). While OBR dentin at a depth of 75 μm was with a mineral density of 23.7% and a higher HIS200 than sound dentin, the reduced $H\mu$ was the result of the transformation of dentin as a relatively homogenous

medium to permit greater light penetration. Enamel is a highly mineralized crystalline structure consisting of 90% to 92% mineral by volume. On the other hand, dentin is a tubular structure that is composed of approximately 50% inorganic material and 30% organic material by volume. In dentin caries, demineralization is followed by the destruction of organic matrix caused by the activity of bacterial proteases.³³ Consequently, it is probable that the organic phase breakdown due to the caries influences the optical property of the substrate resulting in the lower attenuation of the OCT signal when imaged perpendicular to the direction of demineralization progress. The acidic environment created by bacterial acid is thought to facilitate the activation of host-derived matrix metalloproteinases (MMPs) present in dentin.³⁴ Carious dentin was reported to contain active forms of MMP-2, -9, -8, -3, and be able to cleave matrix components such as type I collagen.³⁴ Since collagen is optically nonlinear and is known to scatter light, gelatinized or fragmented collagen appears less scattering³⁵ (Figs. 5 and 8). It is highly probable that mineral-deprived dentin matrix can appear as a dark zone under OCT due to the loss of main scatters in some of the clinical situations.

In this study, SS-OCT detected the enamel demineralization caused by natural caries or bacterial demineralization as an increase in the signal intensity calculated at various degrees

Fig. 8 Distribution of HIS200 and $H\mu$ values at different mineral densities. Polynomial approximation curves were calculated and are shown on the graph. HIS200 values of OBR enamel and carious enamel were higher than the value of sound enamel. In dentin, HIS200 of OBR demineralization and natural caries were mostly higher than the sound dentin value. The $H\mu$ values of demineralized enamel were slightly higher than the sound enamel. However, natural caries showed slightly lower $H\mu$ at low mineral density zone (12% mineral density) and high mineral density zone (over 80% mineral density). The $H\mu$ values for both OBR dentin and carious dentin of were slightly lower than the sound dentin.

of mineral loss. Consequently, even early enamel demineralization displayed as a bright zone in the SS-OCT image. With dentin, a significant increase in HIS200 was detected at a limited depth, although all HIS200 values showed an increasing trend compared with the value for sound dentin. Because dentin is a hybrid substrate containing both organic and inorganic phases, the reaction of the OCT signal due to cariogenic demineralization may be complex especially in clinics.

One of the main advantages of OCT imaging over x-ray radiography is the ability to decrease the radiation dose from visual diagnostic approaches in dentistry. When there is doubt about the existence of a lesion, additional SS-OCT images with an altered position or angle can be obtained immediately. From this standpoint, SS-OCT is obviously the safer diagnostic modality that can be used for dental diagnosis on patients such as pregnant women and young children. Further study is necessary to evaluate the OCT signal generated from demineralized enamel and dentin for the diagnosis of caries.

5 Conclusion

In this study, signal intensity and attenuation coefficient values of SS-OCT in relation to the mineral density were evaluated for demineralized enamel and dentin exposed to *S. mutans* biofilm

in OBR and for natural caries. Both demineralized enamel and dentin showed significant increase in signal intensity and attenuation coefficient over the sound structure from the sagittal scan direction of SS-OCT. For the horizontal scan, the increased SS-OCT signal for various degrees of demineralized enamel were nearly the same, even at the low level of demineralization. In dentin, the attenuation coefficient from the horizontal scan showed a decreasing trend, although significance was detected only at a depth of 75 μm in OBR demineralization.

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