Early Dental Caries and Demineralization Measurements by Using Portable OCT Scanner

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Abstract: There is an increasing need in dental research and clinical practice for accurate measurements of teeth. Currently, methods such as x-rays and quantitative light-induced fluorescence (QLF) are used, but there are problems such as the effects of radiation and limitations in resolution. Optical Coherence Tomography (OCT) used in this study uses near-infrared light, which has no effect on the human body and provides very high resolution in the range of tens of micrometers. OCT allows for non-invasive imaging, making it safer for repeated use and ideal for monitoring caries progression over time. In this study, we developed a portable OCT scanner specialized for dental use and measured and evaluated early caries and demineralization.

1 INTRODUCTION

In dental research and clinical practice, there is an increasing need for precise measurements of the teeth, such as the progression of early caries, caries between adjacent teeth, and cracks on the tooth surface (Colston, 1998; De Melo, 2005; Shimada, 2010; Imai, 2012; Leão Filho, 2013). Currently, methods such as X-ray and quantitative visible light induced fluorescence (QLF) are used, but there are problems such as radiation effects and limited resolution (Shiina, 2003; Shimada, 2020). In recent years, the application of Optical Coherence Tomography (OCT), already commercialized in the field of ophthalmology, to dentistry has attracted attention, and research on OCT for dentistry was initiated by Sumi and colleagues around 2010 (Shimada, 2010; Park, 2018). Non-destructive tomographic imaging of bonded restorations (Makishi, 2011) and non-destructive tomographic imaging using optical coherence tomography (OCT) OCT was commercialized as a medical device for dental use in Japan in 2020. However, due to limitations in probe size, product size and even price, it is currently used more for research purposes than for actual clinical practice.

OCT uses the low-coherence light interference of an SLD as a light source. Cross-sectional images of the target can be obtained in a non-erosive and non-destructive manner, and the depth resolution, which is determined by the coherence length of the light source, is about a few tens of microns, which is higher than that of X-ray or ultrasound measurements.

Currently, high-speed and high-dynamic-range OCTs such as Fourier-domain OCT (FD-OCT) and spectral-domain OCT (SD-OCT) are in practical use, mainly in the medical field, but they are expensive, large, and have complex systems (Colston Jr, 1998). The TD-OCT (Time-Domain OCT) used in this study can be designed independently in terms of the wavelength of the light source used, measurement range and resolution, and it can be configured at low cost. TD-OCT is slower scanning speed than other medical OCTs, but it allows a longer measurement depth and does not require complex and extensive computational processing, as the time information can be directly converted into depth information.

In this study, a portable OCT scanner specially designed with a tiny optical probe for dental uses and its demonstration experiment has been performed to scan, measure, and evaluate caries on extracted teeth. In addition, the teeth were immersed in vinegar to

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reproduce the initial caries state and to measure and evaluate the level of enamel demineralization on the tooth surfaces (Tsai, 2019).

2 DEVICE CONFIGURATION

The optical configuration of the portable OCT scanner developed in this study is shown in Fig.1. The low-coherence light emitted from the SLD($\lambda_0 = 1.3\mu m, \Delta\lambda = 53nm, Anritsu\ Co., Ltd.$) light source is split into two beams by a fiber coupler and directed towards the reference mirror and the measurement target, respectively. The reference optical system of this device utilizes a variable optical path mechanism. By fixing the reference mirror and rotating the reflector, the reflected light is returned to the fiber coupler with a time delay. Meanwhile, the light directed towards the measurement target passes inside the target. The light is scattered (backscattered) back in the original direction by each layer within the measurement target. The light returning from these two optical paths interferes and is received by the Photo Diode (PD). In the receiving circuit, the interference light is converted into an electrical signal with the adequate filtering and magnification, and the waveform can be observed on an oscilloscope.

OCT technology has been widely successful in ophthalmology for detecting and diagnosing eye conditions. The non-invasive nature of OCT, combined with its high resolution, makes it a promising tool for dental applications. In comparison to X-rays, OCT eliminates the risk of radiation exposure, making it safer for repeated use. To uniformly measure the enamel, which is a random medium, a mechanism for moving the probe and a algorithm for processing the oscilloscope signals on a PC are integrated. This allows continuous observation the interference waveform and obtaining average optical properties.

The appearance of the device is shown in Fig.2. It is small, with dimensions of 180mm in width, 240mm in length, and 105mm in height, and weighs approximately 3kg. It operates with a DC power supply, with a rotation reflector for varying the optical path length and an SLD light source output of 2mW[max], making it low in power consumption and be portable. The OCT probe is shown in Fig.3. The numerical aperture (N.A) of the lens used is 0.11, resulting in a lateral resolution of 9.87 μm. The measurement of the distance from the probe and the signal strength indicated that the focal length is 0.8mm.

The probe, intended for intraoral use, is enough small with a diameter of 3.6mm and a length of 12mm, consisting of a single hemispherical lens. This allows for easy handling within the oral cavity, from the anterior teeth to the molars, and both buccal and lingual sides.

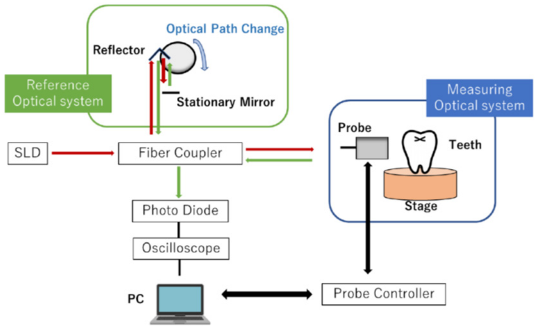


Figure 1: System configuration of TD-OCT.

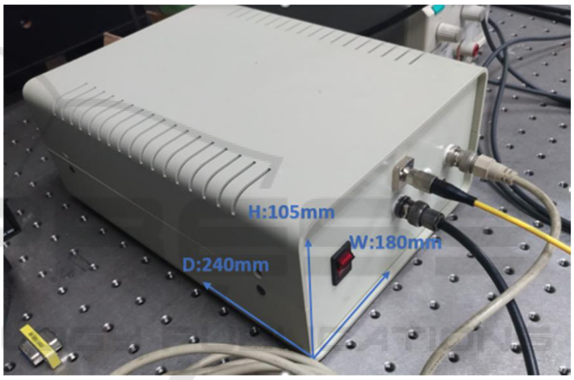


Figure 2: Device appearance of a portable OCT.

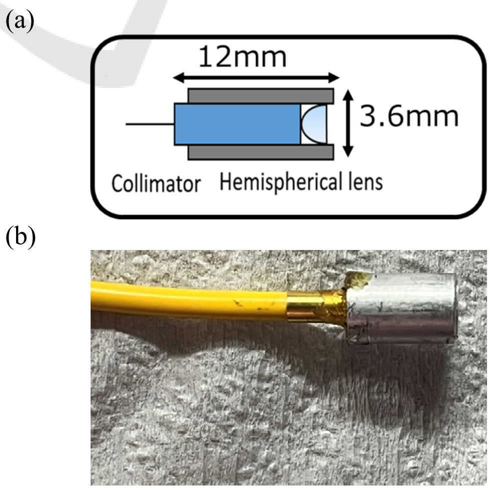


Figure 3: Probe for dental OCT/ (a) Schematic diagram (b) Photograph.

3 EXPERIMENTAL PROCEDURES

The setup for the tooth measurements in this study is shown in Fig.4. First, the extracted tooth is mounted in a hole on the stage so that the emitted light, indicated by the green arrow, is perpendicular to the tooth surface. Next, the probe is scanned horizontally along the tooth in the direction of the red arrow. The measurement interval is set to 1 scan (1 line in depth direction) per 0.20 mm. To capture the fine surface irregularities when measuring the tooth shape, scanning is performed at 1 scan per 0.10mm. However, in order to measure the optical properties within the enamel quickly and uniformly, a wider interval was used. Since the width of the teeth used in the experiment is about 6 to 8 mm, a single measurement can collect about 30 to 40 lines, which is sufficient for the study.

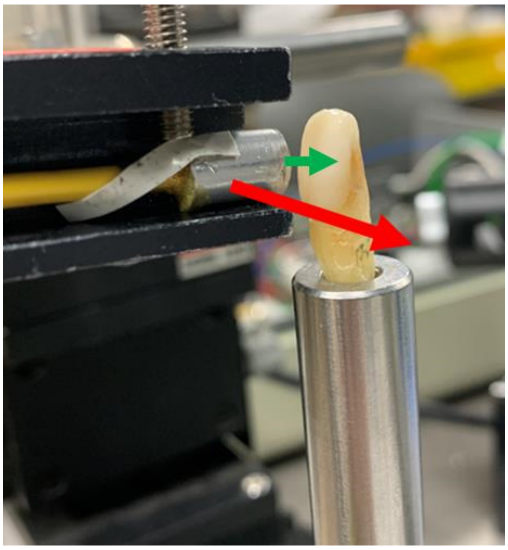


Figure: 4 Optical probe scanning process.

Figure 5 shows photographs of some of the human teeth used for OCT measurements for caries checks and demineralization processing. Extracted human teeth with no visible damage or caries were selected, including a total of 17 teeth from both anterior and posterior regions. The black lines on the surface of the teeth were used as reference marks for measurement. The probe was positioned perpendicular to the tooth surface at these marked positions and the distance between the probe and the tooth surface was adjusted for focus. Measurements were taken only on the enamel side surfaces because the occlusal surfaces were unsuitable due to their irregularities.

Figure 5: Some of the measurement samples of human teeth.

Figure 6 illustrates the workflow of the demineralization experiment. First, healthy teeth were measured with an OCT scanner. After they were immersed in a demineralization solution, they were measured again with OCT, and this process was repeated until the demineralization time reached 36 hours. After each demineralization treatment, the teeth were thoroughly rinsed with water and the surfaces were dried to ensure that no water droplets were present during the measurement. That care was taken not to rub the surface during drying. Fresh demineralization solution was used each time after the teeth were removed. The same positions were measured using reference marks as shown in Fig.5.

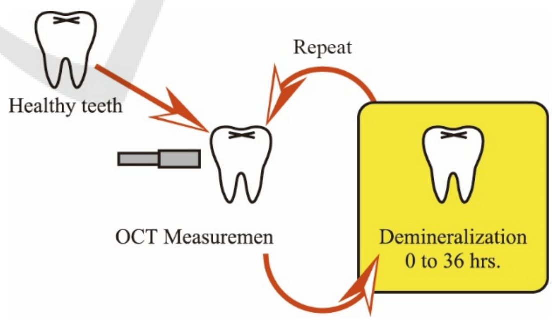


Figure 6: Demineralization Experiment Workflow.

4 EVALUATION METHOD

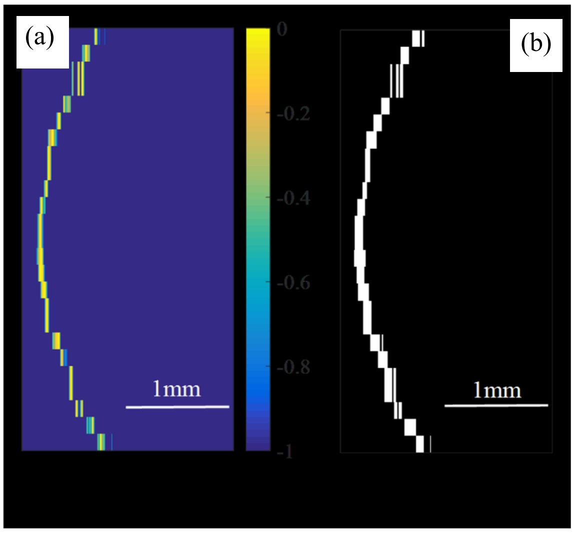
In the field of dentistry, there have been reports that suggest demineralization potentially infiltrate internally using SS-OCT (Damodaran, 2016). During the analysis, it is helpful to consider binarizing the signals using a threshold. In healthy teeth, the OCT signal is initially visible only at the surface, but gradually, it expands under the demineralization. This phenomenon, which is known as superficial demineralization, refers to the early stages of caries progression, where demineralization can be observed spreading in the enamel's surface layer (approximately 0.1 to 0.5 mm). It has been suggested that dental OCT offer a means of detecting early caries that are difficult to confirm visually. However, it should be noted that these results have not yet been subjected to a quantitative evaluation, as they are based solely on comparisons of OCT images.

In this study, we enhance the quality of the raw data by performing a series of processing steps, including focal position correction, distance-squared correction, normalization at the peak position, and natural logarithm processing. We then applied binarization using a threshold to the processed data. As demineralization progresses in the enamel surface layer, it would seem that the signal expands internally within the enamel. This will etch the surface and cause demineralisation but will not cause weakening of the outer enamel and subsequent sub-surface mineral loss. It is helpful to define this range as the demineralization range, and to calculate the average depth. Following normalization, a threshold is set, and areas with values exceeding this threshold are displayed in white. Figure 7 illustrates the alterations in OCT images prior to and following binarization. The threshold setting was informed by the published paper (Damodaran, 2016). The average demineralization depth is calculated by dividing the area of the white region by the horizontal length (corresponding to the vertical axis in Fig.7).

Figure 8 illustrates a typical B-scan result from the demineralization experiment. It seems that the demineralization depth will expand due to the treatment, which could potentially increase the range where interference signals appear. This illustrates how acid gradually erodes the surface, gradually progressing deeper into the enamel. It would seem that the eroded enamel generates a great many fine cavities, which become increasingly porous and thus increase backscattering. For the sake of clarity, we would like to present the demineralization range shown in Fig.8 in a different format. This is done by using a threshold to create a binarized image, which we will show in Fig.9. It is proposed that the areas with color changes in the binarized data be considered as the demineralization depth.

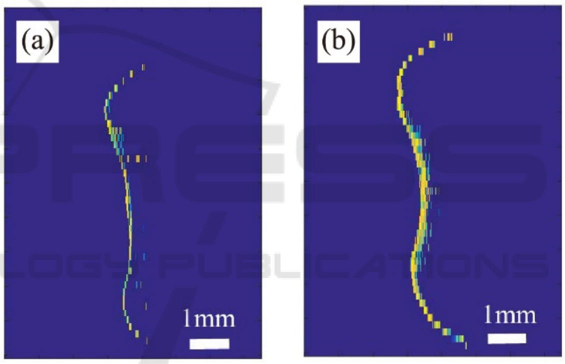
5 MEASUREMENTS OF EARLY CARIES

Figure 10(a) and (b) illustrate the anterior tooth samples utilized for OCT measurement. That the dotted lines in the figures indicate the B-scan measurement position, with measurements taken



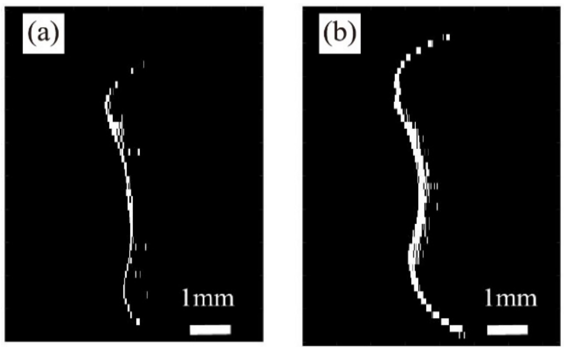
(a) OCT Image immediately after logarithmic processing (b) Binarized OCT image

Figure 7: Changes in OCT images due to binarization.



(a) Before demineralization
(b) After demineralization

Figure 8: Changes in B-scan due to demineralization.



(a) Before demineralization
(b) After demineralization

Figure 9: Binarized B-scan image using threshold.

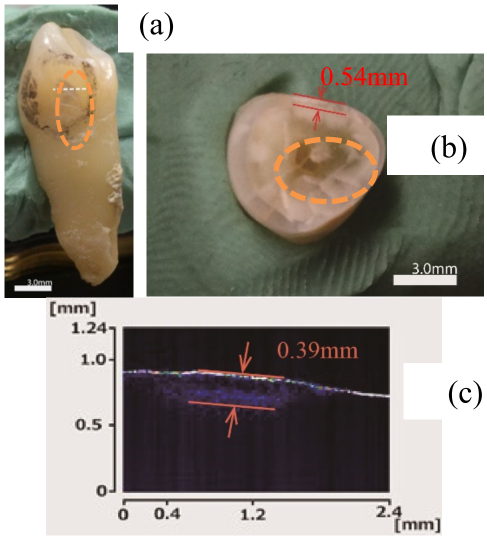
from right to left in the photograph. The measurements were taken in a horizontal direction on the surface. It will be observed that within the dotted circles in Fig.10(a) and (b), these areas appear to be more opaque than other parts. This is an indication of early caries (CO). The results of the measurements across these areas affected by caries are presented in Fig.10(c). In regions where no caries is observed at either end, no signals are detected below the surface. In contrast, in the areas with caries, signals are detectable up to approximately 0.39 mm below the surface. Measuring the thickness of the white opaque area within the dotted circle in Fig.10(b) gives a value of 0.54 mm. Considering the displacement between the section location shown in Fig.10(c) and the measurement location, the results are satisfactory.

Figure 11(a) and 12(a) illustrate the molar samples utilized for OCT measurements. With regard to molar sample B, it was deemed appropriate to take measurements from the occlusal surface. For convenience, the dotted line in each figure indicates the measurement positions, with B-scan measurements taken from right to left across the page.

Figure 11(b) is the measurement results for the molar sample B. It would seem that early caries (C1) will be present in the region indicated by the dotted circle, and staining is visible in the region indicated by the solid circle. In the carious area, it seems that signals from demineralized regions within the tooth is detected in addition to the surface signals. It is helpful to consider the yellow dotted line as a representation of the predicted surface shape in a healthy state. It would appear that the progression of enamel demineralization will result in a collapse of the surface shape.

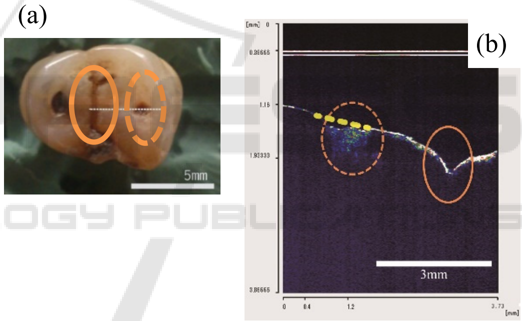
For molar sample C, measurements were taken at intervals of 0.2mm in the direction indicated by the arrows in each figure, with the aim of observing changes in signals at different measurement positions. Fig.12(b) presents the measurement results, with the dotted line results on the left and the results from a 0.2mm shift in the arrow direction on the right.

It is observed that the dotted and solid circle regions in Fig.12(a) appear to correspond to the carious area and the staining, respectively. Figure 12(b) presents the measurement results for sample C, which appear to indicate the presence of early caries (C1) in the dashed circle region. It can be seen from the OCT cross-sectional image that there is a clear progression of internal demineralization, which allows for a quantitative assessment of the depth of progression.



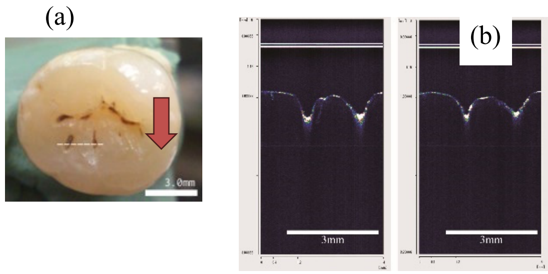
(a) Surface lateral measurement position (b) Cross-sectional view of measurement position (c) Measurement results

Figure 10: Anterior tooth sample A.



(a) Photograph (b) Measurement results

Figure 11: Molar sample B.



(a) Photograph (b) Measurement results

Figure 12: Molar sample C.

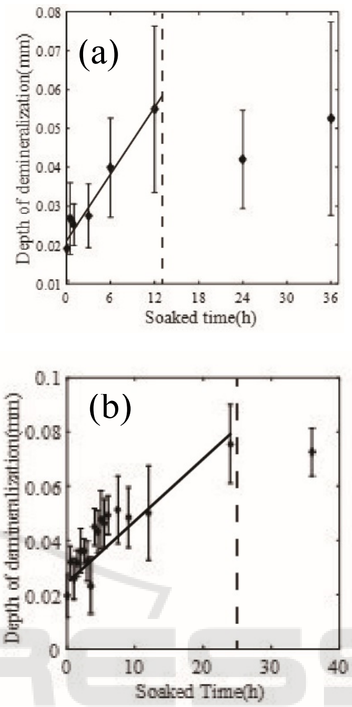
6 MEASUREMENT OF TOOTH DEMINERALIZATION

Figure 13 offers insight into the impact of utilizing undiluted demineralization solution and a 10-fold diluted solution on the depth of demineralization. The horizontal axis represents the immersion time in the demineralization solution, and the vertical axis represents the demineralization depth. With regard to the results obtained with the undiluted solution (pH 2.7), it seems that the demineralization depth will increase in a linear fashion until approximately 12 hours, after which it appears to plateau at a depth of approximately 0.06 to 0.08 mm. This is in line with what the B-scan images appear to show, which seems to indicate that the demineralization process reaches a certain point where it plateaus in the depth direction. With regard to the 10-fold diluted solution, it seems that the increase continues until around 20 hours, after which it appears to plateau at approximately 0.08mm. It seems reasonable to suggest that the longer time taken to reach the plateau is due to the decreased acidity of the diluted solution.

Similarly, it appears that the surface signal intensity will increase gradually until around 12 hours, after which it also seems to reach a plateau. This leads us to the possibility that demineralization is occurring not only internally but also on the surface, with the surface structure potentially changing over time. Furthermore, this observation is of great importance as it highlights the necessity of monitoring both internal and surface changes during demineralization processes to gain a comprehensive understanding of the extent and progression of caries.

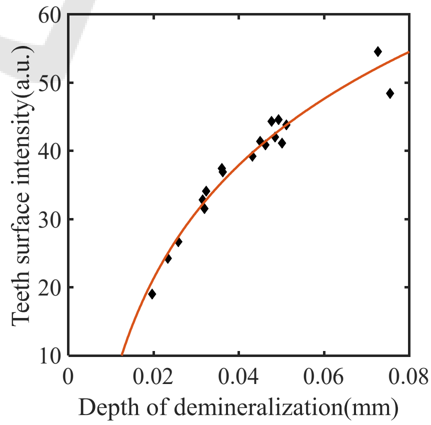
Figure 14 presents a graph with the demineralization depth on the horizontal axis and the surface signal intensity on the vertical axis. It illustrates the results obtained when using the 10-fold diluted solution. The change is logarithmic rather than linear. This result suggests the possibility that there are differences in the pace of erosion within the tooth and the degree of surface erosion. It is the case that the slower increase in surface signal intensity compared to internal erosion is due to differing acid resistance between the internal and surface enamel.

Given the observed difference in acid resistance between the enamel surface and internal, these findings are to be expected. It seems plausible to suggest that the enamel surface will be more acid-resistant than the internal enamel, which could explain these results. Additionally, figure 14 suggests that the surface signal intensity will saturate earlier, indicating that the demineralization solution will first infiltrate the surface before progressing inward. It seems that the initial saturation suggests that surface erosion occurs relatively quickly, followed by a more gradual internal demineralization process. This could be an indication of the layered nature of enamel degradation.



(a) When using undiluted solution (pH2.7)
(b) When using 10-fold diluted solution

Figure 13: Relationship between demineralization time and demineralization depth.



(When Using 10-Fold Diluted Solution)

Figure 14: Relationship between demineralization depth and surface signal intensity.

7 CONCLUSIONS

In this study, we have developed a cost-effective and portable TD-OCT scanner that could potentially offer a more efficient alternative to existing dental OCTs.

For the measurement of early caries, we used human teeth after tooth extraction and evaluated the measured signal in the early caries area. In the measurement of anterior teeth, the depth of the clouded area was measured to be approximately 0.39 mm by OCT, and generally good results were confirmed in comparison with the actual cut surface measurement of 0.53 mm. Although numerical comparisons were not made for the molar area due to the severe surface irregularities, clear differences in measurement signals were observed between the caries-affected and non-caries-affected areas.

We also aimed to gain a deeper understanding of the effects of demineralization on teeth. To assess the effects of demineralization, we immersed extracted human teeth in commercially available vinegar and evaluated changes in demineralization depth, surface signal intensity, and attenuation coefficient as demineralization progressed. We observed that the demineralization depth, surface signal intensity, and attenuation coefficient increased at rates of 2.6 μm/h, 2.7/h, and 0.18 mm^{-1}/h, respectively. After approximately 36 hours, these values appeared to stabilize. The analysis methods were based on previously published methods, and the obtained values were similar to those measured using microscopes.

In order to gain a better understanding of the effects of drying, we conducted an analysis of the OCT signals for both non-demineralized and demineralized teeth after drying. In order to dry the samples, silica gel was used, and the samples were placed in a container with less than 10% humidity for 30 minutes. While non-demineralized teeth showed minimal effects from drying, demineralized teeth exhibited increased demineralization depth (approximately 1.20 times), increased surface signal intensity (approximately 1.33 times), and decreased attenuation coefficient (approximately 0.63 times). It seems that these changes in signals will be attributed to the formation of fine voids in the HA crystals, which are the main component of enamel, due to demineralization. This could allow moisture to enter and exit.

From these results, we were able to gain insight into the changes in OCT signals within teeth caused by early dental caries, demineralization and drying using TD-OCT. Further work could include developing devices for use in clinical settings and devising methods to measure and evaluate in real time within the oral cavity.

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