Measurement of the remaining dentin thickness using optical coherence tomography for crown preparation

Rie FUJITA1, Wataru KOMADA1, Kosuke NOZAKI2 and Hiroyuki MIURA1

1 Fixed Prosthodontics, Department of Restorative Sciences, Graduate School, Tokyo Medical and Dental University, 1-5-45 Yushima, Bunkyo-ku, Tokyo 113-8549, Japan
2 Department of Material Biofunctions, Institute of Biomaterials and Bioengineering, Tokyo Medical and Dental University, 2-3-10 Kanda-Surugadai, Chiyoda-ku, Tokyo 101-0062, Japan
Corresponding author, Wataru KOMADA; E-mail: w.komada.fpro@tmd.ac.jp

This study aimed to investigate the maximum depth imaging and optical properties of the dentin near the pulp by using optical coherence tomography (OCT) and to explore the possibility of measuring the remaining dentin thickness (RDT). Human third molars were used. In experiment 1, the cuspal dentin blocks (0.50-mm to 1.75-mm thickness) were prepared. Each specimen was scanned using OCT. OCT images could be obtained for all specimens with 1.00-mm or less thicknesses. In experiment 2, dentin-pulp complex slices (0.50-mm and 1.00-mm RDT) were prepared. Each specimen was scanned using OCT and micro-computed tomography, and compared. The resulting length change rates of OCT images for the 0.50-mm RDTs were significantly lower than those of the 1.00-mm RDTs. Within the limitations of this study, OCT was effective for measuring the 1.00-mm or less RDT and preventing pulpal injury, while considering the length change rate of OCT image as a variable.

Keywords: Optical coherence tomography, Remaining dentin thickness, Refractive index, Tooth preparation

INTRODUCTION

The key to successful prosthetic treatment of vital teeth is the integral knowledge of the properties, structure, and function of the dentin-pulp complex that constitutes the necessary biological basis for making clinical decisions.

Dentin forms the hard tissue of the dentin-pulp complex, whereas the dental pulp is the soft connective tissue that retains the vitality of dentin. Despite differences in structure and composition, dentin and pulp are integrally connected in the sense that physiologic and pathologic reactions in one of the tissues will also affect the other1. Dentin is the most effective protective barrier to reduce pulpal injury, for example, pulpal inflammation and exposure. The concept of the dentin-pulp complex is well founded and generally recognized4-6. Injury to the pulp may become more intense as a result of tooth preparation. Drill speed, coolant, and operator pressure can all influence pulpal responses. In addition, it has been known for several decades that the remaining dentin thickness (RDT) plays an important role in determining pulpal injury and the repair response required after tooth preparation7,8. Deep tooth preparations expose wider and more dentinal tubules per square millimeter than shallow preparations, which can lead to pulp injury.

Clinically, knowledge regarding RDT is collected through indirect methods such as radiography, and ultrasonic pulse-echo9. However, radiographic procedures possess some limitations related to the presentation of overlapping anatomical structures and emission of ionizing radiation10. Optical coherence tomography (OCT) is a well-known laser technique for providing noninvasive, high spatial resolution images of the biological microstructure. It works similarly to ultrasound but simply uses light waves instead of sound. This technique was initially used in ophthalmology11, in which it has been well developed and is clinically used, but it has also been continuously benefiting other areas, such as cardiology, gastroenterology, dermatology, and cellular engineering12-14. In recent years, some studies have suggested the usability of OCT in dentistry, for example, for the treatment of caries and adaptation of restorations15,16. However, there have been no studies regarding the measurement of RDT by OCT. It is possible to avoid excessive tooth preparation and the pulp injury if the RDT is measured with OCT. The purpose of this study was to investigate the maximum depth imaging of dentin with OCT, as well as the optical properties of dentin near the pulp, and to explore the possibility of RDT measurement using OCT.

MATERIALS AND METHODS

Maximum depth imaging of dentin with OCT

1. Specimen preparation

Ten extracted human third molars, which were free of caries, cracks, and fractures, were used in this study. All teeth were collected after each individual’s informed consent was obtained according to a protocol approved by the Ethical Review Board of Tokyo Medical and Dental University (the confirmation number: 729.2012). They were stored in a refrigerator until the experiment.

Received Oct 29, 2013; Accepted Feb 10, 2014
doi:10.4012/dmj.2013-303   JST JSTAGE/dmj/2013-303
A low-speed saw (Isomet, Buehler, An ITW Co., USA) was used to cut the teeth into blocks. First, the teeth were divided into six pieces in parallel along the long axis of the tooth (Fig. 1). After that, each piece was cut perpendicular to the long axis of the tooth at the cuspal dentin with a corresponding thickness of 0.50 mm, 0.75 mm, 1.00 mm, 1.25 mm, 1.50 mm, or 1.75 mm.

2. OCT system
The swept-source OCT (SS-OCT) system (Dental SS-OCT, Prototype 2, Panasonic Healthcare, Co. Ltd, Japan) used in this study uses a frequency domain OCT technique that interprets the magnitude and coherence of the light from a subject into a depth profile of the subject (Fig. 2). The light source was a high-speed-frequency swept external cavity laser with a center wavelength of around 1,330 nm, a waveband of over 100 nm, and a sweep rate of 30 kHz. Two-dimensional (2D) tomography images (B-scan) were created from serial backscatter (reflectivity) profiles (A-scan) along the surface (Fig. 3). A 2D image has lateral and axial resolutions of 20 µm and 12 µm, respectively, in air, and its size is 2,000×1,019 pixels, with pixel dimensions of 9.0 µm×3.5 µm. This system has a handheld intraoral probe equipped with a charge-coupled device (CCD) camera that enables photographic visualization of the surface that will be scanned in real time.
Fig. 4 OCT images were obtained (a). $Z_0$: the vertical position of the specimen surface; $Z_1$: the vertical position of the reflective surface of the microscope slide; $d$: the thickness of the specimen; and $c_s$: the length change rate of OCT image for the specimen. Two-dimensional tomography (B-scan) image (b) and the corresponding signal intensity profiles (c) of a 0.50-mm dentin block. $Z_2$: the vertical position of the microscope slide as imaged through the specimen. The pointers (→) indicate the mirror reflections between the glass slide and the dentin surface.

3. OCT imaging
Each specimen was placed on a microscope slide (75 mm×25 mm and 1–1.2-mm thickness). The handheld probe was set at a fixed distance from the specimen surface, with the scanning light beam oriented at approximately 90° with respect to the surface. A custom-made jig was mounted on a stage to keep each specimen surface parallel to the probe plane (Fig. 1). OCT images were obtained. Photographic images were obtained from the CCD camera attached to the scanning probe that showed the specimens on the OCT images.

4. OCT image analysis (Measurement of the length change rate of OCT image and signal intensity)
OCT is based on low-coherence interferometry and thus can be used to measure the optical path length (OPL). The length change rates of OCT images are required to convert the optical depth values measured from OCT to real depth values. Figure 4 shows a schematic diagram of the specimen on a microscope slide, on which the vertical position of the specimen surface is $Z_0$, the vertical position of the microscope slide’s reflection surface is $Z_1$, the thickness of the specimen is $d$, and the length change rate of OCT image for the specimen is $c_s$. Figure 4(b) is a 2D tomography image of a specimen (0.50-mm thickness) on a microscope slide that shows the change in the microscope slide’s vertical position that was caused by the specimen. The thickness of the sample could be determined by subtraction of the vertical position of the microscope slide without the specimen ($Z_1$) from that of the specimen surface ($Z_0$) in the OCT image, and the additional OPL can be measured by subtraction of the vertical position of the microscope slide imaged through the specimen ($Z_2$) from that of the specimen surface ($Z_0$). Assuming the OPL of the specimen is $Z_2-Z_0$ and the actual thickness of the specimen ($d$) is $Z_1-Z_0$, we can obtain the following relationship between the thickness and the length change rate of OCT image for the specimen:

$$d=Z_1-Z_0=(Z_2-Z_0)/c_s \tag{1}$$

Therefore, the length change rate of OCT image for the sample can be obtained from Formula (1) as follows:

$$c_s=(Z_2-Z_0)/(Z_1-Z_0) \tag{2}$$

Formula (2) was used to calculate $c_s$.

Figure 4(c) shows the signal intensity profiles corresponding to the marked locations in Fig. 4(b). With OCT, the maximal and minimal signal intensities were large, so the decibel (dB) system was used for quantifying the signal intensity. For the optical field, dB is a logarithmic unit used to describe the ratio between two signal powers ($P_1$ [W], $P_2$ [W]) of a system. Generally, the signal intensity, $L$ (dB), can be expressed as:

$$L=10 \log_{10}(P_1/P_2)$$

that was caused by the specimen. The thickness of the sample could be determined by subtraction of the vertical position of the microscope slide without the specimen ($Z_1$) from that of the specimen surface ($Z_0$) in the OCT image, and the additional OPL can be measured by subtraction of the vertical position of the microscope slide imaged through the specimen ($Z_2$) from that of the specimen surface ($Z_0$). Assuming the OPL of the specimen is $Z_2-Z_0$ and the actual thickness of the specimen ($d$) is $Z_1-Z_0$, we can obtain the following relationship between the thickness and the length change rate of OCT image for the specimen:

$$d=Z_1-Z_0=(Z_2-Z_0)/c_s \tag{1}$$

Therefore, the length change rate of OCT image for the sample can be obtained from Formula (1) as follows:

$$c_s=(Z_2-Z_0)/(Z_1-Z_0) \tag{2}$$

Formula (2) was used to calculate $c_s$.

Figure 4(c) shows the signal intensity profiles corresponding to the marked locations in Fig. 4(b). With OCT, the maximal and minimal signal intensities were large, so the decibel (dB) system was used for quantifying the signal intensity. For the optical field, dB is a logarithmic unit used to describe the ratio between two signal powers ($P_1$ [W], $P_2$ [W]) of a system. Generally, the signal intensity, $L$ (dB), can be expressed as:

$$L=10 \log_{10}(P_1/P_2)$$

3. OCT imaging
Each specimen was placed on a microscope slide (75 mm×25 mm and 1–1.2-mm thickness). The handheld probe was set at a fixed distance from the specimen surface, with the scanning light beam oriented at approximately 90° with respect to the surface. A custom-made jig was mounted on a stage to keep each specimen surface parallel to the probe plane (Fig. 1). OCT images were obtained. Photographic images were obtained from the CCD camera attached to the scanning probe that showed the specimens on the OCT images.

4. OCT image analysis (Measurement of the length change rate of OCT image and signal intensity)
OCT is based on low-coherence interferometry and thus can be used to measure the optical path length (OPL). The length change rates of OCT images are required to convert the optical depth values measured from OCT to real depth values. Figure 4 shows a schematic diagram of the specimen on a microscope slide, on which the vertical position of the specimen surface is $Z_0$, the vertical position of the microscope slide’s reflection surface is $Z_1$, the thickness of the specimen is $d$, and the length change rate of OCT image for the specimen is $c_s$. Figure 4(b) is a 2D tomography image of a specimen (0.50-mm thickness) on a microscope slide that shows the change in the microscope slide’s vertical position that was caused by the specimen. The thickness of the sample could be determined by subtraction of the vertical position of the microscope slide without the specimen ($Z_1$) from that of the specimen surface ($Z_0$) in the OCT image, and the additional OPL can be measured by subtraction of the vertical position of the microscope slide imaged through the specimen ($Z_2$) from that of the specimen surface ($Z_0$). Assuming the OPL of the specimen is $Z_2-Z_0$ and the actual thickness of the specimen ($d$) is $Z_1-Z_0$, we can obtain the following relationship between the thickness and the length change rate of OCT image for the specimen:

$$d=Z_1-Z_0=(Z_2-Z_0)/c_s \tag{1}$$

Therefore, the length change rate of OCT image for the sample can be obtained from Formula (1) as follows:

$$c_s=(Z_2-Z_0)/(Z_1-Z_0) \tag{2}$$

Formula (2) was used to calculate $c_s$.

Figure 4(c) shows the signal intensity profiles corresponding to the marked locations in Fig. 4(b). With OCT, the maximal and minimal signal intensities were large, so the decibel (dB) system was used for quantifying the signal intensity. For the optical field, dB is a logarithmic unit used to describe the ratio between two signal powers ($P_1$ [W], $P_2$ [W]) of a system. Generally, the signal intensity, $L$ (dB), can be expressed as:

$$L=10 \log_{10}(P_1/P_2)$$
With the SS-OCT system that was used in this study, the maximal signal intensity, which was detected, was defined as 70 dB, resulting in a signal-to-noise ratio advantage of 0–10 dB, and the arbitrary signal intensity could be calculated by using the ratio of the arbitrary signal power to the maximal signal power.

For each specimen, the possibility of obtaining an image of $Z_2$ was confirmed. Subsequently, calculation of $c_s$ and measurement of the signal intensity of $Z_2$ were performed for the specimens, from which an image of $Z_2$ could be obtained.

5. Statistical analysis
Data were analyzed by one-way repeated-measures ANOVA followed by Bonferroni’s post hoc test to compare the length change rate of OCT image and signal intensity of $Z_2$ between each thickness. The significance level for the statistical analysis was set at $\alpha=0.05$. The analyses were performed with the SPSS software (12.0J for Windows, SPSS Inc., Chicago, IL, USA).

Dentin-pulp complex imaging compared with OCT and micro-computed tomography

1. Specimen preparation
Ten extracted human third molars, which were free of caries, cracks, and fractures, were used in this study. All teeth were collected after each individual’s informed consent was obtained according to a protocol approved by the Ethical Review Board of Tokyo Medical and Dental University (the confirmation number: 729.2012). They were stored in a refrigerator until the experiment. They were embedded in an epoxy resin (EpoxiCure#208130, Buehler, An ITW Co., USA) (Fig. 5).

A low-speed saw (Isomet, Buehler, An ITW Co., USA) was used to cut the blocks into 1.00-mm slices. The blocks were sliced in parallel along the long axis of the teeth. Two sliced blocks, in which the dentin-pulp complex was observed, were selected. In addition, one of the sliced blocks was trimmed perpendicular to the long axis of the teeth until the occlusal dentin remained at a thickness of 0.50 mm, while another one was 1.00-mm thickness. Gutta-percha points (GC Corp., Japan) were embedded in the sliced block as a guide for the OCT or micro-computed tomography (CT) imaging.

2. OCT imaging
The handheld probe was set at a fixed distance from the occlusal surface, with the scanning light beam oriented at approximately 90° with respect to the occlusal surface. A custom-made jig was mounted on a stage to keep each specimen’s occlusal surface parallel to the probe plane (Fig. 5). OCT images were obtained using the gutta-percha point as a guide.

3. OCT imaging analysis
Figure 6 is a 2D tomography image of the specimen. $Z_2'$ shows the vertical position of the pulp-dentin junction.
in the OCT image. For each specimen, calculation of the OPL in the specimen (Z2'−Z0) and measurements of the signal intensity of Z2' were obtained.

4. Micro-CT Imaging

Micro-CT images were obtained using a micro-focus X-ray CT system (inspexio SMX-100CT, Shimadzu Corp., Japan). Images were obtained employing the following settings: acceleration voltage, 70 kV; current, 30 μA; voxel size, 15 μm/voxel; and matrix size, 1024×1024.

Micro-CT images were obtained using the gutta-percha point as a guide in the same sections of the OCT images.

Z1' shows the vertical position of the pulp-dentin junction in the CT image (Fig. 7). The RDT (Z1'−Z0) for each specimen was calculated, along with the length change rate of OCT image for the specimen (c') using Formula (2).

5. Statistical analysis

Data were analyzed by a two-sided paired t test to compare the length change rate of OCT image and signal intensity of Z2' between each RDT. The significance level for statistical analysis was set at α=0.05. The analyses were performed with the SPSS software (12.0J for Windows, SPSS Inc., Chicago, IL, USA).

RESULTS

Maximum depth imaging with OCT in dentin

The number of specimens for which Z2 was obtained in the OCT images of the dentin slices with thicknesses of 0.50 mm, 0.75 mm, 1.00 mm, 1.25 mm, 1.50 mm, and 1.75 mm were 10, 10, 10, 9, 4, and 3, respectively. The 1.50-mm and 1.75-mm dentin slices were excluded from the statistical analysis because the specimens from which images of Z2 were obtainable were few in number.

The length change rate of OCT image was calculated and signal intensity of Z2 was measured for each specimen. The resulting length change rates of OCT images for the dentin slices with thicknesses of 0.50 mm, 0.75 mm, 1.00 mm, and 1.25 mm were 1.63±0.10, 1.67±0.09, 1.80±0.06, and 1.79±0.16, respectively (Fig. 8). There were significant differences between the following thicknesses: 0.50 mm and 1.00 mm, 0.50 mm and 1.25 mm, and 0.75 mm and 1.00 mm.

The signal intensities of the 0.50-mm dentin, 0.75-mm dentin, 1.00-mm dentin, and 1.25-mm dentin were 30.30±2.98 dB, 22.40±2.31 dB, 18.15±3.33 dB, and 14.83±2.03 dB, respectively (Fig. 9). No significant difference was found between thicknesses of 1.00 mm and 1.25 mm. However, there were significant differences among the other thicknesses.

Dentin-pulp complex imaging compared with OCT and micro CT

As indicated in Fig. 10, the resulting length change
Fig. 10 A comparison of the resulting length change rates of OCT images of the different RDTs. An asterisk indicates a statistically significant difference at $\alpha=0.05$.

![Length Change Rate Graph](image)

Fig. 11 A comparison of the resulting signal intensities of the different RDTs. An asterisk indicates a statistically significant difference at $\alpha=0.05$.

![Signal Intensity Graph](image)

rates of OCT images for the 0.50-mm RDT and 1.00-mm RDT were 1.57±0.07 and 1.77±0.16, respectively. There was a significant difference between the resulting length change rate of OCT image for the 0.50-mm RDT and 1.00-mm RDT.

In addition, the resulting signal intensities of the 0.50-mm RDT and 1.00-mm RDT were 29.17±2.10 dB and 17.67±1.35 dB, respectively. These results are shown in Fig. 11. There was a significant difference between the 0.50-mm RDT and the 1.00-mm RDT.

**DISCUSSION**

The importance of RDT for preventing pulpal injury

The importance of maximizing the RDT after a tooth preparation for reducing pulpal damage has long been established, although the precise relationship between the degree of pulp injury and the RDT is unclear. Deep cavities with small RDTs leave the pulp tissue less protected from preparation trauma and from the chemical activity of dental materials.

In 1984, Stanley suggested that an RDT of 2 mm would protect the pulp from most restorative procedures. In 1991, Pameijer, Stanley, and Ecker reported that an RDT of 1 mm would better protect the pulp tissue from the cytotoxic effects of zinc phosphate and resin-modified glass ionomer materials during the luting process. In 2000, it was suggested that these were cautious estimates and that excessive tooth preparations, carefully cut down to 0.50 mm, appeared to have only a limited effect on the underlying odontoblast survival.

It was reported that specimens that had dentin thicknesses of 0.30–0.40 mm could yield Z$_2$ OCT images. In this study, all specimens that had dentin thicknesses of 1.00 mm or less could yield Z$_2$ or Z$_3$ OCT images. Therefore, this study proposed that OCT could obtain the image of the dentin-pulp complex with 1.00-mm or less thickness and would be useful for reducing pulpal injury.

Measurement of RDT

Some methods exist to measure RDT. A few examples of these methods include the optical microscope and electron microscope. However, these methods necessitate that the specimens be sliced. With these methods, it is difficult to obtain tomography images in similar sections as that of OCT images, because of the cutting allowance. In this study, a micro-focus X-ray CT system was used because arbitrary section images were obtained in a non-destructive manner. Thus, for the same part, specimens can be measured several times.

Length change rate of OCT image

The refractive index is a factor affecting the OPL, as well as an important optical parameter for biological tissues including teeth, because each biological tissue has its own refractive index. There are some methods for measuring the refractive index of biological tissue that is turbid and has strong scattering. They are classified into two kinds: “focus-tracing method” and “optical path length matching method”. The optical path length matching method had the advantages of a simple, fast measurement, and higher accuracy compared with that of the focus-tracing method. In this method, specimens with 0.30-mm to 0.40-mm thickness were used, and the same Formula was used for the length change rate of OCT image. In this study, specimens with a 0.50-mm to 1.75-mm thickness were used. We utilized the length change rate of OCT image, not the refractive index, because the specimens were thick and because it was necessary to consider the directionality and heterogeneous components of the dentin tubules.

The refractive index is the ratio of the speed of light in vacuo to the speed of light through a subject. Each subject has a different refractive index because the speed of light through each subject is different. The refractive index is also influenced by the wavelength. The center wavelength of the SS-OCT system in this study was around 1,330 nm.

A characteristic of human dentin is the presence of tubules. Dentinal tubules form around the odontoblast processes and traverse the entirety of the dentin from the dentinoenamel junction (DEJ) and the cementum-
dentin junction (CDJ) to the pulp\textsuperscript{12}. They are slightly tapered, with the wider portion situated toward the pulp.

It was reported that a change in scattering with respect to a change in the structural orientation of dentin results in a variable refractive index\textsuperscript{18}. Hariri reported that the average dentin refractive index was 1.55 using a 1,330-nm center wavelength; however, a significant decrease in the refractive index was detected in locations within the dentin block, in which the dentinal tubules were parallel or were at a small angle to the direction of the light beam, compared to that of the dentin block, in which the dentinal tubules were perpendicular and oblique\textsuperscript{19}. Within the dentin block, the refractive index of the parallel, perpendicular, and oblique dentinal tubules (to the direction of the light beam) was 1.49±0.07, 1.60±0.04, and 1.56±0.08, respectively. Several studies have investigated the role of tubules in the scattering and transport of light\textsuperscript{21,22}. Kienle et al. explained that light was guided along the tubules in a direction close to that of the tubule because of multiple scattering by the tubules. Thus, the angle between the direction of the light beam and the dentinal tubule was large, the length change rate of OCT image was greater. In this study, the cuspal dentin near the pulp horn was used and the dentinal tubules were oblique to the direction of the light beam\textsuperscript{23}. Therefore, it was possible to increase the length change rate of OCT image in this study. Moreover, the larger the RDT becomes, the greater the increase in the angle between the direction of the light beam and the dentinal tubule, because the tubules near the pulpal horn curve become radial as they extend from the DEJ to the pulp\textsuperscript{23}, and the greater the increase in the length change rate of OCT image.

Moreover, each individual dentinal tubule is an inverted cone with the smallest dimensions at the DEJ and the largest dimensions at the pulp\textsuperscript{12,22,23,28}. The dentin consists of calcium hydroxyapatite (70 weight percent [wt%]), 47 volume percent [vol%]), organic material (20 wt%, 30 vol%), and water (10 wt%, 21 vol%)\textsuperscript{29}. The water content of the dentin near the DEJ is about 1 vol%, while that of the dentin near the pulp is about 22 vol%. Each component has a different refractive index. For example, the refractive index of calcium hydroxyapatite is 1.62, while the refractive indices of organic material and water are lower than that of calcium hydroxyapatite\textsuperscript{27}. Therefore, it is possible that the mineral or water content affect the refractive index in each region of the dentin. Furthermore, Snell’s law works when light passes through a medium of a lower to higher refractive index or conversely. According to Snell’s law, when light passes through a medium of a higher to lower refractive index, the OPL is greater\textsuperscript{28} (Fig. 12). The more the dentin thickness increases, the greater the increase in the difference in the mineral or water content and the length change rate of OCT image.

In the OCT system, the greater the increase in the thickness of the dentin, the greater the increase in the length change rate of OCT image, because of the directionality and heterogeneous components of the dentin tubules.

**Clinical measurement of RDT using OCT**

When RDT is measured clinically, it can be obtained from Formula (1), as “the OPL divided by the length change rate of OCT image.” The resulting length change rates of OCT images for the 0.50-mm RDT and 1.00-mm RDT in this study were 1.57±0.07 and 1.77±0.16, respectively. Assuming that the OPL was 0.89 mm, the RDT would be 0.50 mm if the length change rate of OCT image for the dentin were set at 1.77. In addition to these assumptions, the RDT would be 0.56 mm if the length change rate of OCT image for the dentin were set at a lower value. Therefore, if the length change rate of OCT image for the dentin was set at a lower value, it would be possible to increase an excessive tooth preparation and the pulpal injury because a higher RDT is a criterion for evaluation. It is probably best that the length change rate of OCT image for the dentin is set as a higher value for preventing pulpal injury, if 0.50–1.00 mm of RDT is required.

In addition, the signal intensity was inversely proportional to the dentin thickness in this study. It was suggested that signal intensity was one of the key factors to understanding RDT.

**CONCLUSION**

Within the limitations of this *in vitro* study, the following conclusions were drawn:

1. OCT could obtain an image of the dentin-pulp complex with a 1.00-mm or less thickness. It is useful to evaluate the RDT during a tooth preparation.
preparation. The length change rate of OCT image is necessary in order to image and measure the RDT correctly, after an OCT image is clinically scanned.

2. The length change rate of OCT image for a 0.50-mm-thick dentin was lower than that for a 1.00-mm-thick dentin.

ACKNOWLEDGMENTS
This study was partly supported by the Grants-in-Aid for Scientific Research from the Japanese Society for the Promotion of Science (No. 23390432).

REFERENCES
1) Mjor IA, Odont D. Pulp-dentin biology in restorative dentistry. Part 2: initial reactions to preparation of teeth for restorative procedures. Quintessence Int 2001; 32: 537-551.
2) Stephen Cohen KMH. Pathways of the pulp. 9th ed. St. Louis: Mosby; 2006. p. 460-540.
3) Pashley DH. Dynamics of the pulpo-dentin complex. Crit Rev Oral Biol Med 1996; 7: 104-133.
4) Vongsavan N, Matthews B. Changes in pulpal blood flow and in fluid flow through dentine produced by autonomic and sensory nerve stimulation in the cat. Proc Finn Dent Soc 1992; 88 suppl 1: 491-497.
5) Murray PE, About I, Lumley PJ, Franquin JC, Remusat M, Smith AJ. Human odontoblast cell numbers after dental injury. J Dent 2000; 28: 277-285.
6) Murray PE, About I, Lumley PJ, Smith G, Franquin JC, Smith AJ. Postoperative pulpal and repair responses. J Am Dent Assoc 2000; 131: 321-329.
7) Murray PE, Smith AJ, Windsor LJ, Mjor IA. Remaining dentine thickness and human pulp responses. Int Endod J 2003; 36: 33-43.
8) About I, Murray PE, Franquin JC, Remusat M, Smith AJ. Pulpal inflammatory responses following non-curious class V restorations. Oper Dent 2001; 26: 338-342.
9) Morozumi M. Measurement of the dentin thickness with an ultrasonic pulse-echo technique: The longitudinal sonic velocity in human dentin. J Jpn Prosthodont Soc 1985; 29: 15-29.
10) Huang D, Swanson EA, Lin CP, Schuman JS, Stinson WG, Chang W, Hee MR, Flotte T, Gregory K, Puliafito CA. Optical coherence tomography. Science 1991; 254: 1178-1181.
11) Boppart SA, Tearney GJ, Bouma BE, Southern JF, Brezinski ME, Fujimoto JG. Noninvasive assessment of the developing Xenopus cardiovascular system using optical coherence tomography. Proc Natl Acad Sci USA 1997; 94: 4256-4261.
12) Garberoglio R, Brannstrom M. Scanning electron microscopic investigation of human dentinal tubules. Arch Oral Biol 1976; 21: 355-362.
13) Pierce MC, Strasswimmer J, Park BH, Cense B, de Boer JF. Advances in optical coherence tomography imaging for dermatology. J Invest Dermatol 2004; 123: 458-463.
14) Natsume Y, Nakashima S, Sadr A, Shimada Y, Tagami J, Sumi Y. Estimation of lesion progress in artificial root caries by swept source optical coherence tomography in comparison to transverse microangiography. J Biomed Opt 2011; 16: 071408.
15) Senawongse P, Pongprueksa P, Harnirattisai C, Sumi Y, Otaki M, Shimada Y, Tagami J. Non-destructive assessment of cavity wall adaptation of class V composite restoration using swept-source optical coherence tomography. Dent Mater J 2011; 30: 517-522.
16) Stanley HR. Design for a human pulp study. I. Oral Surg Oral Med Oral Pathol 1968; 25: 633-647.
17) Pameijer CH, Stanley HR, Ecker G. Biocompatibility of a glass ionomer luting agent. 2. Crown cementation. Am J Dent 1991; 4:134-141.
18) Hariri I, Sadr A, Shimada Y, Tagami J, Sumi Y. Effects of structural orientation of enamel and dentine on light attenuation and local refractive index: an optical coherence tomography study. J Dent 2012; 40: 387-396.
19) Wang X, Zhang C, Zhang L, Xue L, Tian J. Simultaneous refractive index and thickness measurements of bio tissue by optical coherence tomography. J Biomed Opt 2002; 7: 628-632.
20) Meng Z, Yao XS, Yao H, Liang Y, Liu T, Li Y, Wang G, Lan S. Measurement of the refractive index of human teeth by optical coherence tomography. J Biomed Opt 2009; 14: 034010.
21) Kienle A, Michels R, Hibst R. Magnification—a new look at a long-known optical property of dentin. J Dent Res 2006; 85: 955-959.
22) Walton RE, Outhwaite WC, Pashley DF. Magnification—an interesting optical property of dentin. J Dent Res 1976; 55: 639-642.
23) Antonio N. Ten Cate’s oral histology: Development, structure and function. 7th ed. St. Louis: Mosby; 1998. p. 203-209.
24) Fosse G, Saede PK, Eide R. Numerical density and distributional pattern of dentin tubules. Acta Odontol Scand 1992; 50: 201-210.
25) Olsson S, Olo G, Adamczak E. The structure of dentin surfaces exposed for bond strength measurements. Scand J Dent Res 1993; 101: 180-184.
26) Hargreaves KM, Goodis HE, Seltzer S. Seltzer and Bender’s dental pulp. Hanover Park: Quintessence Pub Co; 2002. p. 63-93.
27) Nelson W. Taylor CS. Microscopic and x-ray investigations on the calcification of tissue. J Biol Chem 1929; 81: 479-493.
28) Keating MP. Geometric, physical, and visual optics. 2nd ed. Woburn: Butterworth-Heinemann; 2001. p. 1-11.