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Abstract. Coronal tooth lesions, such as caries, enamel cracking, and composite resin restoration cavities, have been observed by optical coherence tomography (OCT). This pilot study was performed to verify whether OCT could reveal details of root canals filled with resin core build-up. A dual-cure, one-step, self-etch adhesive system-bonding agent (Clearfil Bond SE ONE, Kuraray Noritake Dental) and dual-cure resin composite core material (Clearfil DC Core Automix ONE, Kuraray Noritake Dental) were used according to the manufacturer's instructions in root canals. OCT was performed at three stages of the core build-up: after the post space preparation, after bonding application, and after resin core fabrication. The cementum was removed in the cementum absent group and the root was left untreated in the cementum present group. Bubbles were observed in the resin cores and gaps formed between the resin core and dentin. In the cementum absent group, the internal structure of the root could be visualized clearly compared with the cementum present group. The root internal structure could be observed by OCT and the image became clearer when cementum was removed. © 2014 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JBO.19.4.046004](https://doi.org/10.1117/1.JBO.19.4.046004)]

Keywords: optical coherence tomography; nondestructive testing; resin core build-up; self-etch adhesive; tooth root canal; dentin; cementum.

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1 Introduction

A core build-up method using casting, molding materials, and prefabricated posts is performed in order to improve fitness and maintenance of the prosthesis in severely broken down teeth. In the past, casting metal was mainly used for core build-up; this method requires sound tooth substance removal to obtain a satisfactory fit of the metal core and dowel to the abutment tooth and there is a high risk of root fracture.¹ A resin core build-up method, which has excellent tooth conservation and resistance to root fracture, has been increasingly used in recent years. However, the prosthesis is often detached at the interface of the resin build-up core and abutment tooth² because adhesion of resin to root canal dentin is weak compared to that of coronal dentin.³⁻⁵ Since the conditions of root canal dentin are completely different from the coronal dentin, a detailed study on the adhesion aspects in root canal is needed.

Evaluation of adhesion is conventionally done by shear or tensile bond strength test and morphological observation by scanning electron microscope (SEM) and/or transmission electron microscope (TEM). In these methods, distortion (artifact) may occur in the bonding interface during sample preparation. In addition, if the bonding interface is mechanically weak, specimens might fracture and the evaluation may provide no data. In recent years, microcomputed tomography (μ CT) is often used as a nondestructive method for root canal observation.⁶⁻⁸ It is a relatively new technique in the field of reproducible imaging and is based on the collection of two-dimensional projections of x-rays through a specimen, which are then used to reconstruct a three-dimensional image. However, the

measurement procedure is time-consuming and there is a risk of radiation exposure.

Optical coherence tomography (OCT) is a device capable of obtaining precise tomographic images of the tissue without invasion.⁹ OCT is based on the principle of the optical interferometer, which uses a near-infrared reflected light that passes well through living tissue and the apparatus can provide details of the structure ~ 3 mm inside from the surface in real time. Studies have reported the use of OCT in dentistry for observation of caries,^{10,11} soft tissue,¹¹⁻¹³ enamel cracks,¹⁴ evaluation of fit of composite resin to cavity,^{11,15} and observation of root canal wall.¹⁶ Nevertheless, studies to date have not evaluated the bonding interface between resin core and root canal dentin. Therefore, the aim of this study was to observe the adhesive interface between root canal and resin core build-up nondestructively using OCT.

2 Materials and Methods

2.1 Tooth Preparation

A total of six caries-free human teeth, including incisors and premolars with single and straight root canals, extracted due to periodontal reasons, were selected for this experiment [Fig. 1(a)]. The crown was removed using a low-speed diamond wheel saw (Maruto Instrument, Fukuoka, Japan) at the level of the cemento-enamel junction under copious water irrigation. Root canal preparation was performed using K-file (MANI, Tochigi, Japan) [Fig. 1(b)] and obturated by lateral condensation using gutta-percha points and noneugenol sealer (Canals N,

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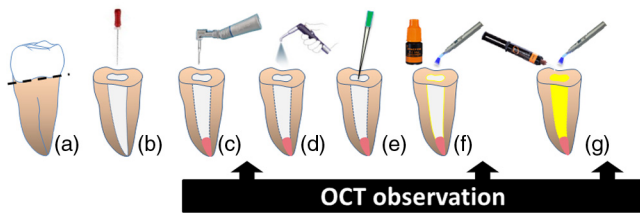


Fig. 1 Specimen preparation and optical coherence tomography (OCT) observation timing. (a) The crown was removed. (b) The root canal was prepared and obturated. (c) The root canals were enlarged. (d) The canals were rinsed. (e) The canal was dried well. (f) The adhesive was applied and light cured. (g) All post spaces were filled with dual-cure resin composite core material.

Showa Yakuhin Kako, Tokyo, Japan). The teeth were then stored in distilled water at 37°C for 24 h.

After immersion, the specimens were randomly divided into two main groups ($n = 3$) based on the presence or absence of cementum. The cementum was removed by a diamond quality bur (FG 102R, Shofu Inc., Kyoto, Japan) and the surface was polished by waterproof abrasive paper (# 600) in the cementum absent group. The cementum present group did not receive these treatments.

2.2 Resin Core Build-Up

For both groups, the root canals were enlarged with low-speed preparation drills (FR drill, Tokuyama Dental, Tokyo, Japan) to a working length of 10 mm from the cemento-enamel junction [Fig. 1(c)]. Following preparation, the canals were rinsed with 3% ethylenediamine tetra-acetic acid solution (Smear Clean, Nipponshika Yakuhin, Yamaguchi, Japan) for 2 min and followed by sodium hypochlorite gel application (AD gel, Kuraray Noritake Dental, Okayama, Japan) for 1 min. The canal was finally irrigated with distilled water [Fig. 1(d)] and then dried well with paper points [Fig. 1(e)].

A dual-cure one-step self-etch adhesive system-bonding agent (Clearfil Bond SE ONE, Kuraray Noritake Dental) was used according to the manufacturer's instructions for bonding to root canal dentin [Fig. 1(f)]. Excess adhesive resin at the bottom of the canal was removed using a paper point. The adhesive was then light-cured for 20 s with a cordless light-emitting-diode curing light (Mini LED3, Satelec, Merignac, France), which had a maximal light density of 2200 mW/cm². All post spaces were filled with dual-cure resin composite core material (Clearfil DC Core Automix ONE, Kuraray Noritake Dental) [Fig. 1(g)].

2.3 OCT Observation

The swept-source OCT system (OCM1300SS, Thorlabs Inc., New Jersey) operated in polarization-sensitive mode without phase retardation has been used to acquire two-dimensional and three-dimensional images of *ex vivo* biological tissues. The system consists of the swept source engine, imaging module, and imaging probe with articulated probe mount for flexible use. The laser contained within the swept source engine has a central wavelength of 1330 nm with a bandwidth of 110 nm, scanning rate of 20 kHz, and image acquisition time of 50 frames per second. The system is capable of acquiring respective axial and lateral resolutions of 12 and 5.6 μm .

OCT observation was performed at three stages for each specimen: after the post space preparation, after bonding

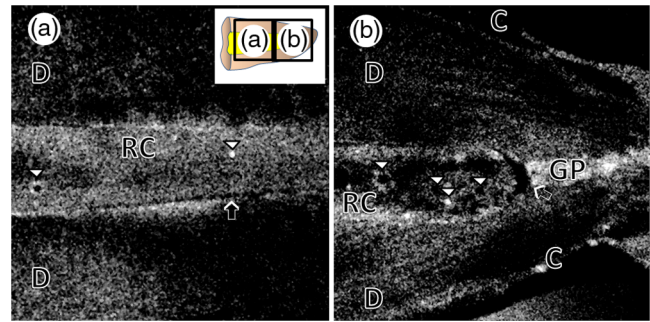


Fig. 2 OCT images of cementum present group after resin core build-up. (a) Coronal side. The resin core material is observed in enlarged canal space. Bubbles are observed in the resin core (arrow heads) and a gap is formed between the resin core and dentin (arrow). (b) Apical side. The gap is formed at the bottom of the enlarged space (arrow). More bubbles are trapped in the resin core (arrow heads), as compared to that of the coronal side. D, dentin; C, cementum; RC, resin core; GP, gutta-percha.

application, and after resin core fabrication. The observation area was 5 mm in the tooth axis direction and 3 mm in the horizontal direction for detailed view. Therefore, the image was taken two times for the tooth crown side and root apex side, i.e., to include an entire post space in the range of 10 mm tooth axis direction.

3 Results

OCT observation revealed the root structure (cementum, dentin) and inside of the root (resin core, gutta-percha) (Fig. 2). Bubbles were observed in the resin core and a gap had formed between the resin core and dentin and at the bottom of the enlarged space. On comparing images of the coronal side [Fig. 2(a)] with that of the apical side [Fig. 2(b)], there were more bubbles in the post space, which tended to increase toward the root apex.

The internal structure of the root appeared blurred in the cementum present group, probably because the cementum surface reacted strongly and information could not be obtained [Fig. 3(a)]. On the other hand, in the cementum absent group, the internal structure of the root was visualized more clearly as compared with the cementum present group, and bubbles inside cured resin cores could also be observed more clearly [Fig. 3(b)]. Distribution tendency of the bubbles in the resin core and gap formation between dentin and resin core, also affected by

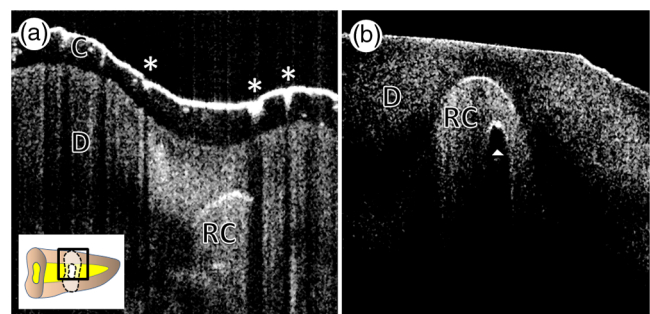


Fig. 3 OCT images of cementum present group and cementum absent group. (a) Cementum present group. When the waves emitted react strongly with cementum, internal information is not obtained because the signal is lost (asterisk). (b) Cementum absent group. The bubbles in resin core are clearly observed (arrow). D, dentin; C, cement; RC, resin core.

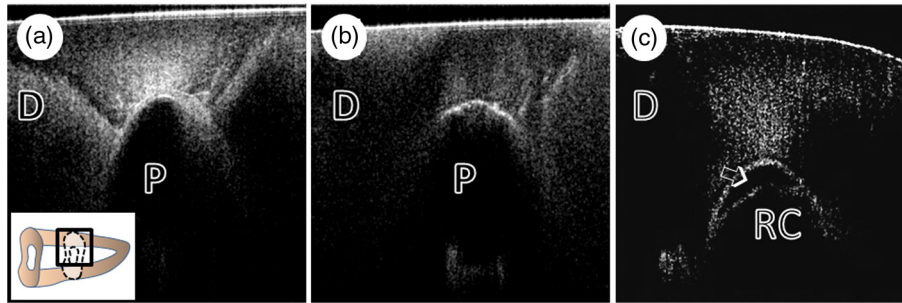


Fig. 4 OCT images of each step of resin core build-up (cementum absent group). (a) After post space preparation [see Fig. 1(c)], the interface between dentin and post space is clearly indicated. The post space is filled by air. (b) After bonding application [see Fig. 1(f)], the post space is still filled with air; however, bonding resin is present on dentin surface. (c) After resin core fabrication [see Fig. 1(g)], a gap is observed between bonding resin and resin core (arrow). D, dentin; P, post space; RC, resin core.

cementum, were observed in the same manner in all samples ($n = 3$).

OCT was performed in three stages of core build-up: after the post space preparation, after bonding application, and after resin core fabrication (Fig. 4). OCT image of the specimen after post space preparation revealed the interface between dentin and post space clearer than that of the specimen after bonding application. Bonding resin on dentin surface was observed. The post space was filled by resin core material; however, a gap was found between bonding resin and resin core.

4 Discussion

OCT enables observation of internal tissue without destroying the sample, helps understand the structure, and allows for observation of samples in real time. Transition to nondestructive testing from destructive inspection is essential for the next generation evaluation of adhesion; thus, the authors focused on OCT. In the present study, the structure of the root canal was clarified in detail by OCT observation (Fig. 2). Since OCT exhibits the characteristics of noninvasiveness, high resolution, objectivity, and concurrency, it has been reported as the latest medical imaging technology in several fields of medicine in recent years.^{15,17,18} In OCT, a tomographic image is built by applying an interference of near-infrared laser between the reference light and reflected light at various portions of each tissue.¹⁹ With OCT, the differences in structure and subtle composition of the organization can be clearly observed because the light is reflected at the interface of materials having different refractive indices.^{20–22} Sumi observed caries, enamel cracking, and composite resin restoration cavity with OCT, and concluded that OCT could be used for clinical applications in dentistry because it provides a high-resolution image and is noninvasive, fast, and nondestructive.⁹ The present study revealed that OCT observation was feasible not only in coronal tooth but also in root canals.

It has been reported that the bonding effectiveness to tooth root canal dentin is inferior to that of tooth crown dentin.^{23,24} OCT observation in the present study indicated a clear gap formation between dentin and resin core, which suggests poor bonding effectiveness to root canal dentin.^{25,26} Moreover, since the gap is greater toward the apical side, it becomes certain that the adhesive–root dentin interface problem in the apical area is more serious than that of the coronal area. The reasons for low bonding effectiveness to root canal dentin include the influence of residual moisture in the root canal,²⁶ insufficient polymerization light reaching the resin,^{27,28} and a very high C-factor.^{29,30}

Although the present results confirmed the presence of a gap, the origin could not be located. In the future, if formation of the gap can be shown in real time by using OCT (i.e., live mode), it might be very useful to understand the mechanism of the gap formation and help to develop methods to improve the bonding effectiveness in the apical area. In addition, as for the large number of bubbles in the resin core, there is a possibility of water or air getting trapped in the root canal when the resin core was filled or in the syringe when the resin is filled. Matsumoto et al. reported that a large number of bubbles were observed in resin cores in the apical side,²⁶ and OCT images of the present study also gave similar results. Although the resin core build-up method is used more frequently in clinical situations than before, there is still room to improve the method based on the results of the present study. Bubbles present inside the cured resin cores cause a reduction in physical properties of the cured resin cores themselves, and gaps between the resin core and dentin undoubtedly lead to a reduction in force maintenance. Considering the prognosis of the resin core build-up method, future improvements in materials and procedures are necessary to avoid the occurrence of gaps and bubbles. As an idea of reversal, if the adhesion in the apical area is insufficient, the question is whether the post hole preparation method currently used in clinics is effective. In other words, a long post hole may not be necessary during the root canal preparation. This might reduce the incidence of root fracture, which is currently a problem in clinics.^{31,32}

Dental adhesives have been evaluated by shear or tensile bond strength tests and/or morphological observation using TEM and SEM for a long time. These methods have some shortcomings; it is difficult to evaluate specimens if the bonding effectiveness is low, in particular because external forces to the bonding interface cannot be avoided during preparation of the specimen. For example, if such a specimen is subjected to conventional bonding effectiveness evaluation, the specimen will surely fracture and measurements cannot be performed. A nondestructive test that does not exert strong force on the sample is very useful because it is possible to capture phenomena that cannot be observed in conventional adhesion evaluation. The μ CT is one nondestructive testing method by which a tomographic image of a wide range can be obtained as compared with OCT. In the present study using OCT, the number of voids and gaps was higher in the apical region compared to the coronal region, as Wolf et al. reported previously using μ CT.⁶ The resolution of OCT used in the present study was $\sim 10 \mu\text{m}$ and that of μ CT used in published studies, which observed inside of the

tooth root, ranged from 6.64 to 28 μm .^{6,8} Although the resolutions of OCT and μCT were considered to be almost the same, the images of μCT were clearer than that of OCT.^{6,7} Moreover, the distribution of voids in root canals could be quantified in the previous studies.^{6,7}

When OCT is used to observe the internal root for evaluation of the condition of enamel remaining on the root surface, the dentin inside appears blurred due to strong reflection that occurs at the cementum layer (Fig. 3). To our knowledge, the present study is the first to clearly reveal the impact of cementum on OCT observation. Moreover, each adhesive step of resin core build-up was clarified by observing cementum removed from specimens for the first time (Fig. 4). Strong reflection from the root surface might be caused by surface roughness. The surface roughness in the cementum absent group was less than that in the cementum present group because the surface was polished with waterproof abrasive paper after removal of the cementum, thereby reducing scattering. Even when the cementum was removed, the depth to which OCT could be observed was limited to 3 mm.³³ The OCT used in the present study is the one used in the ophthalmic field, with the same conditions that are basically set for observation of soft tissues. In the future, it will be necessary to determine the most optimal conditions required to clearly observe hard tissue. Nonetheless, higher intensity and longer wavelength of light may not be required to observe hard tissues more clearly using OCT.³⁴

The present study showed that it was difficult to visualize the root canal distinctly by OCT used in the ophthalmic field, especially when it was covered with cementum. To observe the root canal more distinctly, the tooth should be mechanically grinded to get close enough to the root canal in most cases. It is considered that further development is required in order to obtain an image with high quality with OCT, although its advantages include observation in real time and no risk of radiation exposure. Thus, it may be said that the insufficient penetration depth of OCT makes it impractical to be applied *in vivo*.

5 Conclusions

Tooth roots were observed by OCT to examine the adhesive-dentin interface of resin core build-up. The root internal structure could be examined by OCT and the image became clearer when cementum was removed. In the cementum removed group, bubbles in the resin cores and gaps between resin and dentin were observed.

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Biographies of the authors are not available.