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Nondestructive observation of teeth post core-space using optical coherence tomography: comparison with microcomputed tomography and live images

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Abstract. No previous reports have observed inside the root canal using both optical coherence tomography (OCT) and x-ray microcomputed tomography (μCT) for the same sample. The purpose of this study was to clarify both OCT and μCT image properties from observations of the same root canal after resin core build-up treatment. As OCT allows real-time observation of samples, gap formation may be able to be shown in real time. A dual-cure, one-step, self-etch adhesive system bonding agent, and dual-cure resin composite core material were used in root canals in accordance with instructions from the manufacturer. The resulting OCT images were superior for identifying gap formation at the interface, while μCT images were better to grasp the tooth form. Continuous tomographic images from real-time OCT observation allowed successful construction of a video of the resin core build-up procedure. After 10 to 12 s of light curing, a gap with a clear new signal occurred at the root-core material interface, proceeding from the coronal side (6 mm from the cemento-enamel junction) to the apical side of the root. [DOI: 10.1117/1.JBO.20.10.107001]

Keywords: optical coherence tomography; x-ray microcomputed tomography; nondestructive testing; resin core build-up; tooth root canal.

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1 Introduction

The resin core build-up method has recently gained popularity due to its excellent tooth conservation and its root fracture resistance. Some clinical studies have also shown that the survival rate is significantly higher for direct resin core restoration with a prefabricated post than for a conventional cast-metal core.[1] On the other hand, post debonding has emerged as the most frequent mode of failure for resin core build-up restorations in the clinical setting.[2] *In vitro* testing of bond strength has revealed a gradual decrease from the coronal to the apical side of the root canal, and morphological observations have clarified that polymerization and moisture control at the apical portion of the root canal remain insufficient.[3] For these reasons, resin bonding to root canal remains questionable due to stability issues.

Adhesion is conventionally evaluated using either testing of bond strength or morphological observation under electron microscopy. The first method requires cutting a sample, and distortion artifacts may arise at the bonding interface during sample preparation. Moreover, a specimen with a mechanically weak bonding interface could fracture, and the subsequent evaluation will provide no data.

Optical coherence tomography (OCT) and x-ray microcomputed tomography (μCT) are now in wide use for nondestructive testing. OCT is a promising imaging technique capable of obtaining precise tomographic images of the tissue without invasion.[4] OCT was developed according to the principle underlying the optical interferometer, and utilizes near-infrared reflected light that passes through living tissue. This method can provide real-time structural details up to 3 mm below the surface. Our research group has previously examined resin core build-up in the root canal by OCT, clearly revealing the root structure (cementum, dentin) and inside of the root (resin core, gutta-percha).[5] Likewise, μCT provides another nondestructive method of root canal observation.[6–8] In this relatively new modality, two-dimensional (2-D) projections of x-rays passing through a specimen are incorporated into a three-dimensional (3-D) image. This technique has provided the ability to investigate the quality of root fillings on a detailed scale without destroying the object.[7]

Up until now, although comparisons of OCT and μCT in coronal dentin have been reported,[9] no reports have described inside the root canal of the same sample using both OCT and μCT. The purpose of this study was thus to clarify both OCT and μCT image properties from observations of the same root canal after resin core build-up treatment. As OCT allows for observation of samples in real time, there was also a possibility that gap formation could be shown in real time using OCT (i.e., live mode). The purposes of the present study were to investigate: (1) whether the information provided from μCT observation and OCT observation are the same; and (2) whether gap formation between root canal dentin and resin core can be shown in real time/live mode using OCT.

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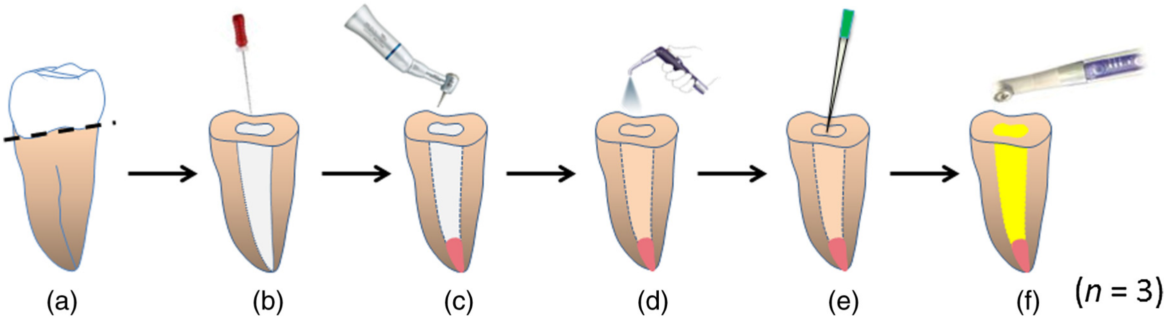

Fig. 1 Specimen preparation. (a) The crown was removed. (b) The root canal was prepared and obturated. (c) The root canal was enlarged. (d) The canal was rinsed. (e) The canal was dried well. (f) All post spaces were filled with dual-cure resin composite core material and light-cured.

2 Materials and Methods

2.1 *Tooth Preparation*

Specimens in the present study included three caries-free human teeth, with single and straight root canals, that had been extracted for periodontal reasons. A low-speed diamond wheel saw (Maruto Instrument Co., Fukuoka, Japan) with copious water irrigation was used to remove the crowns at the level of the cemento-enamel junction. Cementum on the root was removed using a diamond quality bur (FG 102R; Shofu, Kyoto, Japan) and the surfaces of the teeth were polished with waterproof abrasive paper (#600; Sankyo Rikagaku, Saitama, Japan) [Fig. 1(a)]. Root canals were prepared using a K-file (MANI, Tochigi, Japan) [Fig. 1(b)] and were obturated by lateral condensation with gutta-percha points and a noneugenol sealer (Canals N; Showa Yakuhin Kako, Tokyo, Japan). Prepared teeth were stored in distilled water at 37°C for 24 h. Using a low-speed preparation drill (FR drill; Tokuyama Dental, Tokyo, Japan), root canals were enlarged to a working length of 10 mm from the cemento-enamel junction [Fig. 1(c)].

2.2 *Resin Core Build-Up*

After completing preparation, each canal was rinsed with a 3% ethylenediamine tetra-acetic acid solution (Smear Clean; Nipponshika Yakuhin, Yamaguchi, Japan) for 2 min, followed by application of sodium hypochlorite gel (AD gel; Kuraray Noritake Dental, Okayama, Japan) for 1 min. Finally, each canal was irrigated with distilled water [Fig. 1(d)] and dried using paper points [Fig. 1(e)]. For bonding to root canal dentin, a dual-cure one-step self-etch adhesive system-bonding agent (Clearfil Bond SE ONE; Kuraray Noritake Dental) was used according to the instructions from the manufacturer. Any adhesive resin that remained at the bottom of the canal was removed using a paper point. Using a cordless light-emitting diode curing light (Mini LED3; Satelec, Merignac, France) at a maximal light density of 2200 $\mathrm{mW/cm^2}$, the adhesive was cured for 20 s. All post spaces were filled with dual-cure resin composite core material (Clearfil DC Core Automix ONE; Kuraray Noritake Dental), followed by light curing for 40 s [Fig. 1(f)].

2.3 *Optical Coherence Tomography Observation*

The swept-source OCT (SS-OCT) system (OCM1300SS; Thorlabs, Newton, New Jersey) operated in polarization-sensitive mode without phase retardation has been used to acquire 2-D and 3-D images of biological tissues *ex vivo*. The swept source engine of the SS-OCT contains a laser with a central wavelength of 1330 nm, a bandwidth of 110 nm, a scanning rate of 20 kHz, and an image acquisition rate of 50 frames/s. This system is capable of acquiring an axial resolution of 12 μm and a lateral resolution of 5.6 μm.

For each specimen, OCT observation was performed after post space preparation, after bonding application, and after resin core fabrication. Detailed observations were collected in an area 5 mm in the tooth axis direction and 3 mm in the horizontal direction. Two images were, therefore, taken; once for the tooth crown side and once for the root apex side, i.e., to include the entire post space in the range of 10 mm in the tooth axis direction.

2.4 *X-Ray Microcomputed Tomography Observation*

The three specimens used for OCT observation were also observed using μCT (R_mCT2; Rigaku, Tokyo, Japan). The x-ray source operated at 90 kV and 160 μA, with a scan time of 17 s, and image range and resolution of 20 mm × 20 mm and 40 μm, respectively, for the whole sample, or 5 mm × 5 mm and 10 μm, respectively, for the apical part.

2.5 *Real-Time Optical Coherence Tomography Observation*

Sixty seconds of live images of the resin core build-up procedure from core material insertion to the end of about 40 s of light curing was taken using a spectral-domain OCT (SD-OCT) system (TELESTOII; Thorlabs). The laser contained within the spectral-domain engine has a central wavelength of 1.31 μm with a bandwidth of 170 nm, and a scanning rate of 76 kHz. The system is capable of acquiring respective axial and lateral resolutions of 7 and 5.5 μm, respectively. Three specimens were prepared with the same materials and method as OCT and μCT observation. The self-etch adhesive system-bonding agent was applied according to the instructions from the manufacturer and light-cured before taking the live images. The representation range was set to include the apical area of the sample, and a video was created from continuous tomographic images.

3 Results

3.1 *Optical Coherence Tomography and X-Ray Microcomputed Tomography Observation Images of the Same Samples*

OCT observation revealed the inside of the root (resin core, gutta-percha), and bubbles were observed in the resin core, with formation of a gap between the resin core and dentin and a gap at the bottom of the enlarged space (Fig. 2). Observation by μCT also revealed the inside structure of the root (Fig. 3). Comparison between μCT and OCT images of the same sample suggested that OCT images were superior for confirming gap formation at the interface, while μCT images were better to grasp the form. In addition, image properties with both methods showed similar details in all samples ($n = 3$).

3.2 *Real-Time Optical Coherence Tomography Observation*

Continuous tomographic images from real-time OCT allowed successful construction of a video of the resin core build-up procedure (Fig. 4). Figure 5 shows static images of characteristic steps in the video. Before core material insertion, the interface between root dentin and post core space which is filled with air is clearly indicated [Fig. 5(a)]. The clear signal disappears on core material insertion [Fig. 5(b)]. After several tens of seconds of light curing, a new clear signal occurs at the root-core material interface and proceeds from the coronal side to the apical side of the root [Fig. 5(c)].

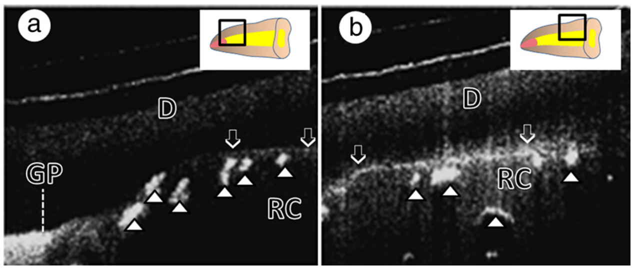

Fig. 2 Optical coherence tomography (OCT) images of the tooth root after resin core build-up. (a) Apical side. Gutta-percha is observed in the enlarged canal space. The differences in structure and composition can be clearly observed. Bubbles are observed in the resin core with strong signal (arrowheads). Line signals (arrow) indicate gap formation between the resin core and dentin. (b) Coronal side. D: dentin, GP: gutta-percha, RC: resin core.

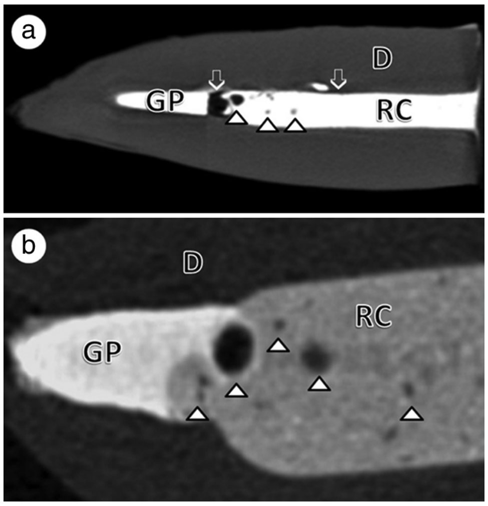

Fig. 3 Images from x-ray microcomputed tomography (μCT) of the tooth root after resin core build-up. (a) Whole sample. Image range of 20 mm × 20 mm, resolution of 40 μm. The resin core material and gutta-percha in the enlarged canal space and bubbles in the resin core (arrowheads) are observed more clearly than in OCT images (see Fig. 2). The gap formed between the resin core and dentin (arrow) is not clear as in OCT images. (b) Apical side. Image range, 5 mm × 5 mm; resolution, 10 μm. No gap is observed in this specimen. D: dentin, GP: gutta-percha, RC: resin core.

On OCT reobservation after taking the video, the starting point of the signal was found approximately 4 mm from the bottom part of the post space (i.e., 6 mm from the cemento-enamel junction) [Fig. 6(a)]. A clear signal was observed in only one specimen, and additional μCT observations of the same specimen did not clarify any information in the same areas [Fig. 6(b)]. No signal was observed in the other two specimens.

4 Discussion

Our research group has previously examined resin core build-up in the root canal by OCT.[5] That previous study revealed that the internal structure of the root was visualized more clearly in a cementum-absent group, as compared with a cementum-present group. The cementum was, therefore, removed from the root surface in the present study, allowing the inside of the root (resin core, gutta-percha) and the gap and bubble formation to be clearly observed by OCT (Fig. 2). Conversely, μCT of specimens provided good visualization of tooth dentin, sealant material, and gutta-percha.[6–8] All different components of the root canal filling, such as gutta-percha and core materials, provided different gray-scale levels, and could be distinguished and assigned to the filling material used.[6] In the present study, μCT observation also revealed the inside structure of the root (Fig. 3).

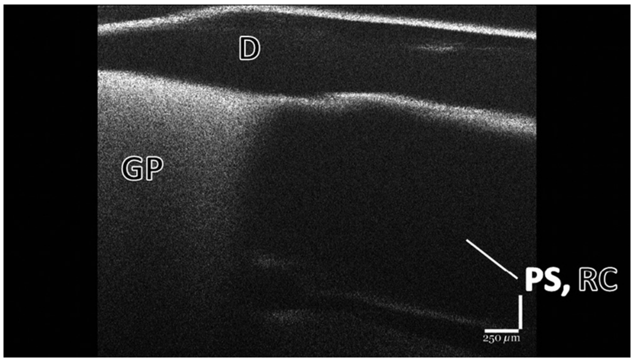

Fig. 4 Video of the resin core build-up procedure constructed from real-time OCT. The self-etch adhesive system-bonding agent was applied and light-cured before taking the video. The video is provided from continuous tomographic images of OCT and edited in triple speed. After several tens of seconds of light curing, a new clear signal becomes apparent at the root-core material interface and proceeds from right (coronal side) to left (apical side). D: dentin, GP: gutta-percha, PS: post space, RC: resin core. (Video 1, MOV, 13.8 MB) [URL: http://dx.doi.org/10.1117/1.JBO.20.10.107001.1].

This is the first report to describe the same roots after resin core build-up using both OCT and μCT at almost the same resolution. The μCT resolution used in this study was 40 or 10 μm. Axial and lateral resolutions were 12 and 5.6 μm for SS-OCT, and 7 and 5.5 μm for SD-OCT, respectively. Images from those modalities showed that OCT images were superior for confirming gap formation at the interface, while μCT images were better for grasping the form. With OCT, differences in structure and subtle compositions of the organization were clearly observed, because light was reflected at the interface of materials with different refractive indices.[10–12] The refractive indices of dentin, resin and air are 1.540 ± 0.013, 1.5-1.6 and 1.0, respectively.[13,14] The dentin-resin interface is thus unclear in OCT

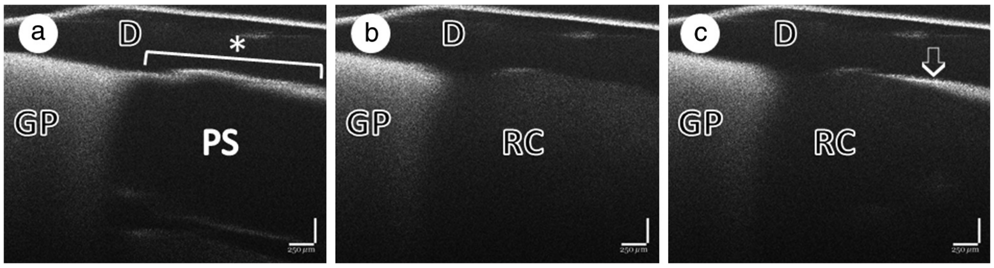

Fig. 5 Individual images of characteristic steps in the video. (a) Before core material insertion, the interface between root dentin and the post core space is clearly indicated because light is reflected at the interface between materials of different refractive indices (i.e., dentin and air) (asterisk). (b) After core material insertion, the clear signal between dentin and the space disappears. (c) After several tens of seconds of light curing, the new clear signal at the root-core material interface (arrow) proceeds from right (coronal side) to left (apical side). D: dentin, GP: gutta-percha, PS: post space, RC: resin core.

observation. However, if a gap forms and the inside of the gap is filled with air, OCT detects this as a strong signal. X-rays from μCT do not react to such differences in refractive indices.[10,11] On the other hand, since observation depth is not limited for x-rays, μCT can provide information on deep parts and μCT images thus depict almost a real form (Fig. 3). These results clearly indicate that the information provided from μCT and OCT observations are not the same. Other differences between OCT and μCT are the time required ($\text{OCT} < \mu\text{CT}$) and radiation exposure (none for OCT).

Gap propagations were successfully captured on video using the distinguishing characteristics of OCT (i.e., real-time observation and better gap indication) (Figs. 4, 5). Since gaps are mostly observed at the bottom of the post space and the nadir is the biggest,[5] gap propagation has been speculated to start from the bottom. However, the gap arose from around the middle of the root and progressed toward the bottom in our study. Ende et al.[15] observed cylindrical cavities filled with a flowable composite using μCT 3-D nonrigid image registration applied to sets of two subsequent μCT images, before and after polymerization, to calculate the displacements and strains caused by polymerization shrinkage. They found that all vector fields showed a nonuniform displacement pattern, irrespective of cavity size. Particularly in large cavities, a twofold displacement pattern was recorded with downward and upward shrinkage directions for the upper-most and bottom-most 2 mm of composite, respectively.[15] This finding clearly showed that polymerization shrinkage is complicated and the post space receives more severe effects of polymerization shrinkage because of the high C-factor. In the present study, gap formation possibly caused by polymerization shrinkage was clearly observed in live mode using OCT, but not by μCT (Fig. 6).

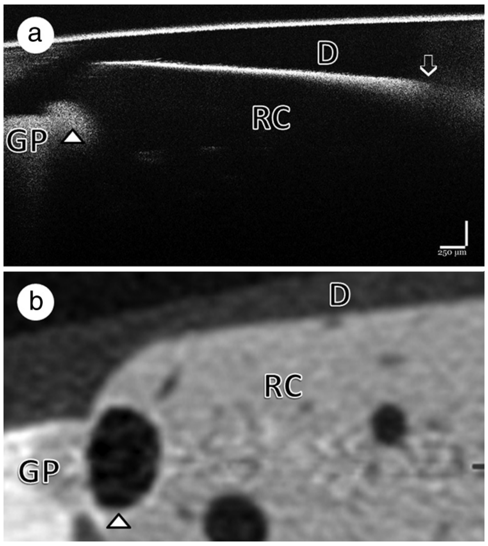

Fig. 6 Reobservation with OCT and μCT at 24 h after taking the video (same specimen). (a) On OCT reobservation, the starting point of the gap (arrow) is approximately 4 mm from the bottom part of the post space (i.e., 6 mm from the cemento-enamel junction). Another signal observed at the bottom of the post space indicates the existence of bubbles. (b) On μCT reobservation of the same specimen, the gap between dentin and resin core is not clear in this image. Clear bubble formation is observed (arrowheads). D: dentin, GP: gutta-percha, RC: resin core.

Two types of OCT were used in the present study. Although SD-OCT and SS-OCT systems follow the same fundamental principles, they apply distinctly different technical approaches to the production of OCT interferograms. The lack of moving parts in SD-OCT systems allows high-mechanical stability and low-phase noise. The availability of a diverse range of cameras has enabled the development of SD-OCT systems with different imaging speeds and sensitivities. SS-OCT systems, on the other hand, rapidly generate the same type of interferogram using a frequency swept light source and photodetector. Rapid sweeping of the swept laser source means that high-peak powers at each separate wavelength can be used to illuminate the sample, providing greater sensitivity with a lower risk of optical damage.[16] SS-OCT was used for comparison with μCT and SD-OCT was used for real-time observations, as SD-OCT offers a higher axial scan rate compared to SS-OCT on this occasion.

In clinical situations, insertion of a post made with fiber or metal in the post space is common. However, using posts doubles the number of adhesive interfaces (i.e., dentin-resin and resin-post), and the post might result in the formation of artifacts on observation. Focusing solely on the interface between dentin and resin core materials would be difficult. We, therefore, decided not to use a post in the present study, as in the previous study.[3] Moreover, the amount of composite will be larger if a post is not used, increasing the configuration stress.

Various reasons for resin core build-up failure have been identified. For example, bonding to root canal dentin is hampered by limited visibility, morphological characteristics,[17] unfavorable conditions regarding the application of adhesive techniques[18] and the comparably high C-factor inside the root canal.[19] In the present study, gap formation starting from the middle part of the root was indicated by OCT live/video mode. This clearly indicated that the configuration factor cannot be ignored in resin core build-up failure. Our research group previously evaluated the bonding effectiveness of one resin core build-up system bonded to root canal dentin in terms of microtensile bond strength.[3] Bond strength data indicated that the value decreases from the middle part of root specimens. The gap started at 6 mm from the cemento-enamel junction in the present study. Post length over 6 mm thus may not play an important role in retention. Better yet, a shorter post might reduce the incidence of root fracture, which is currently a significant problem in clinics.[20,21]

Debonding within class I cavities has been reported to often occur at the bottom of the cavity.[22,23] This has often been attributed to weaker bonding to dentin than to enamel, making the composite more likely to detach from deeper dentin regions.[24] Moreover, some clinicians and researchers believe that configuration starts from the part nearest the light cure unit and polymerization shrinkage behavior progresses toward the light cure unit. The findings obtained from the present study that the formation of the gap progresses in the root at approximately 6 mm from the light irradiation device, therefore, represents a new discovery. Our research here serves as a pilot study for investigations with great potential in terms of improving resin composite cores through OCT imaging. Further studies are needed to identify factors that increase the gap or prevent gap formation using nondestructive methods to quantitatively evaluate different core systems and polymerization methods.

In dentistry, OCT has great potential for use as a new imaging modality because it is a cutting-edge option for tomographic measurement, capable of creating nondestructive, high-resolution images at high speed. For example, the diagnosis of caries is currently mainly performed using visual and x-ray inspection, both of which are simple diagnostic methods. However, visual inspection does not allow determination of the internal characteristics of the potentially carious tooth and diagnosis is thus greatly influenced by the skill and experience of the individual dentist. On x-ray inspection, accurate determination of depth in the buccolingual direction is difficult, and exposure to x-rays carries some degree of risk. OCT allows multiple chairside observations and facilitates objective diagnosis with noninvasive imaging of the intraoral environment. This modality is thus considered to be warranted for the next generation of diagnostic devices in the dental fields. The clinical use of OCT diagnostic techniques will undoubtedly improve the future of dental treatment.

5 Conclusions

1. As a result of comparisons between μCT and OCT images of the same sample, OCT images were found to be superior for confirming gap formation at the interface, while μCT images were better to grasp the form.
2. Clear gap formation approximately 6 mm from the cemento-enamel junction (not from the bottom) could be observed on live/real-time OCT images.

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Biographies for the authors are not available.