

The Ability of Optical Coherence Tomography to Characterize the Root Canal Walls

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Abstract

A detailed understanding of the complexity of root canal systems is imperative to ensure successful root canal therapy. The aim of this study was to evaluate the ability of an optical coherence tomography (OCT) system in imaging root canal walls after endodontic preparation and to correlate these images to histologic sections. Ten extracted mandibular incisors were prepared to size 50 with K-files and Gates Glidden drills. A three-dimensional OCT scan was made with a rotating optical fiber probe inside the root canal. All teeth were sectioned at 5 and 7 mm from the apex and viewed through a microscope. Histologic sections were compared with the corresponding OCT output. All oval canals, uncleaned fins, risk zones, and one perforation that was detected by histology were also imaged by OCT. OCT proves to be a reliable method to image root canals and root dentin in a nondestructive way. This technique holds promise for full in vivo endodontic imaging. (*J Endod* 2007;33:1369–1373)

Key Words

Histology, intracanal imaging, optical coherence tomography, root canal

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Modern imaging techniques are clinically applied during root canal treatment, but important information over inner canal anatomy and dentin thickness is still limited to in vitro observations. Moreover, more than 50% of lower incisors show long-oval form (ratio of long/short canal diameter ≥ 2) 5 mm from the apex (1), which requires special considerations in cleaning and obturation (2). One difficulty in treating oval or curved canals is the chance of strip perforations because of the short distance between the inner canal wall and the periodontal ligament. In these so-called “risk zones,” the clinician is often faced with the challenge to sufficiently clean and enlarge the root canal space while not perforating the mesial or distal wall (3). Current clinical imaging techniques cannot give reliable information on this aspect.

Optical coherence tomography (OCT) is a new diagnostic medical imaging technology that was first introduced in 1991 (4). Since then, it has become a standard tool in ophthalmology and promising imaging method for intracoronary atherosclerosis detection (5). For example, most heart attacks are caused by sudden ruptures of unstable arterial plaques that cannot be detected by using conventional imaging modalities. OCT has the potential to identify these arterial plaques and differentiate stable plaque from unstable. In addition, it is an attractive technique for the early identification of gastrointestinal malignancies, including the esophagus, stomach, and colon (6). Recently, optical in vivo biopsy, providing microscope-quality images in which cell function can be distinguished, is one of the most challenging fields of OCT application (7).

OCT combines the principles of an ultrasound with the imaging performance of a microscope; although an ultrasound produces images from backscattered sound “echoes,” OCT uses infrared light waves that reflect off the internal microstructure within the biological tissues. Using the principle of low-coherence interferometry, it achieves a depth resolution of the order of 10 μm and an in-plane resolution similar to the optical microscope. By scanning the probe along the imaged specimen while acquiring image lines, a two-dimensional or three-dimensional image is built up. The OCT light source has a wavelength of 1300 nm. Visible light that has a shorter wavelength is prone to a higher level of scattering and absorption and produces a shallower imaging depth (8). The frequencies and bandwidths of infrared light are significantly higher than medical ultrasound signals, resulting in increased image resolution (9). In endoscopic OCT imaging, near-infrared light is delivered to the imaging site (usually blood vessels) through a thin fiber. The imaging tip contains a lens-prism assembly to focus the beam and direct it toward the vessel wall. The fiber can be retracted inside a catheter sheath to perform a so-called “pullback,” allowing the user to make a stack of cross-sections, scanning the investigated vessel lengthwise. Modern OCT systems reach a 6-mm imaging depth, with 8- μm resolution, at 50 to 80 frames per second.

OCT potential in dentistry was not overlooked. OCT images of hard and soft tissues in the oral cavity were compared with histologic images using an animal model showing an excellent match (10). In another study, Otis et al (11) discussed the clear depiction of periodontal tissue contour, sulcular depth, connective tissue attachment, and marginal adaptation of restorative materials to dentin, concluding that OCT is a powerful method for generating high-resolution, cross-sectional images of oral structures. Amaechi et al (12) and Baumgartner et al (13) described the recognition of caries with OCT. Recently, Lantis Laser, Inc (Denville, NJ) gained license to LightLab Imaging’s intellectual property portfolio (Westwood, MA) related to OCT in the field of dentistry. OCT could provide dentists with an unprecedented level of image resolution to assist in the evaluation of periodontal disease,

dental restorations, and in the detection of caries. Commercial development of chair-side OCT dental system is already underway (www.lantislaser.com). The purpose of this experiment was to evaluate the ability of an OCT system to provide important information on the root canal walls using histologic sections as control.

Materials and Methods

Preparation of Teeth

Ten extracted single-rooted mandibular incisors were selected. A radiograph was taken from two angles to verify a single canal. Teeth with open apices or large carious lesions were excluded. Each tooth was accessed coronally with a diamond bur (FG 173; Horico, Berlin, Germany), and the canal opening was enlarged with Gates Glidden drills #3 and #4, which were inserted 4 and 3 mm into the canal, respectively. The canal was instrumented to a size 50 stainless steel K-file (Dentsply Maillefer, Ballaigues, Switzerland). Irrigation with 2% NaOCl using a 26-G needle followed after every instrument so that a total of 15 mL of solution was used per tooth. Each canal was then rinsed with sterile saline. For endodontic imaging, the probe's tip has to be placed inside the root canal (Figs. 1 and 2) so that the distal end is inserted through the apex. The apical constriction was opened thus with #45 K-file to allow the optic fiber to penetrate through the canal.

Test Setup

OCT pullback scans were performed by using a LightLab Imaging M2-CV system in combination with an ImageWire 2 catheter. This system is designed for intracoronary imaging in atherosclerotic plaque diagnosis. It is commercially available for clinical use in cardiac catheterization laboratories. The catheter consists of a 2-m long optical single-mode fiber inside a protective sheath, with a diameter of 0.5 mm. The imaging depth in water is 3.3 mm. The axial and transverse image resolutions are 14 and 25 μm, respectively. The imaging guidewire is integrated into an imaging catheter, which is connected to a motor (Fig. 1). Both rotational and horizontal movements of the catheter could be performed, allowing the fiber to be pulled inside the imaged canal in an apical-coronal direction while rotating. This movement is also used in cardiovascular imaging and is commonly referred to as “pullback.”

The tooth was placed in a water bath to improve the optical match between the catheter and the tooth. Motorized “pullbacks” from the apex to the coronal opening were performed, with a speed of 1 mm/s and 10 rotations per second, using 312 lines per frame and 760 samples per line. The result is a stack of images with a spacing of 100 μm. These images were stored as “audio video interleave” files for visual inspection. All teeth were sectioned at 5 and 7 mm from the apical area with a saw microtome (Leica Microsystems SP1600, Wetzlar, Germany). Slices were then viewed through a stereomicroscope (Zeiss Stemi SV6; Carl Zeiss, Göttingen, Germany) by using a cold light source (KL 2500 LCD,

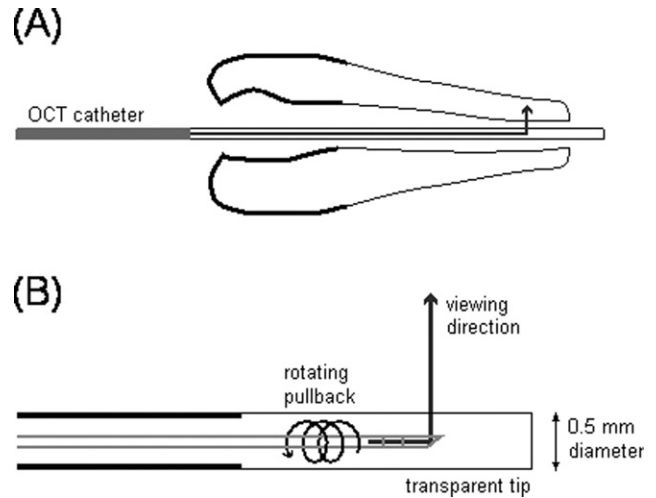


Figure 2. (A) The OCT catheter inside the root canal. (B) A rotating needle with a transparent tip is situated inside the catheter and serves both as a light source and as the receiver, transmitting the reflected beams to the imaging computer.

Carl Zeiss). Pictures were taken with a camera (Axio Cam, Carl Zeiss) at a magnification of ×12 and compared with the corresponding OCT images at the same level. Canal diameters were measured in cross-sections and in the OCT images and were identified as oval when the ratio of long to short canal diameter was ≥1.5. “Risk zone” was defined as dentinal wall thinner than 1 mm.

Results

Results are summarized in Table 1 and Figures 3 to 6. All oval canals, uncleaned fins, risk zones, and one perforation that was histologically detected were also visualized with OCT.

Discussion

The results show excellent correlation between the histologic images and the OCT output. Risk zones were created in 30% of the teeth at 5 mm from the apex, and one root was perforated. The large master file (#50) and the anatomy of the roots that were used (lower incisors) could explain this large incident.

The use of novel imaging techniques is gaining a lot of attention in the field of endodontics. New computed tomography methods prove to be more accurate in the evaluation of bone lesions than conventional radiography (14). Similarly, canal morphology (15), root fractures (16), tooth anatomy (17), and the interface between the root canal and filling materials (18) were successfully shown with different computed tomography techniques. These methods use ionizing radiation, which could be harmful at higher doses when used in vivo. Furthermore, two major disadvantages are limiting the successful application of these methods for intracanal imaging: First, the resolution is usually not suitable for microscopic-level imaging. Digital dental radiography systems

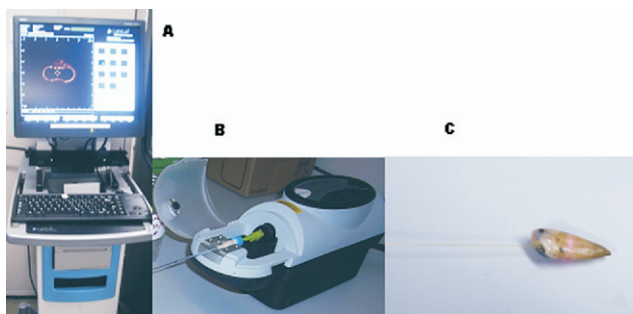


Figure 1. (A) The OCT screen and machine. (B) The motor connected to the catheter. (C) The activated OCT catheter inside the root canal.

TABLE 1. Various Clinically Relevant Parameter Observed in Histology and OCT Images at 5 mm and 7 mm from the Apex

	Histology		OCT	
	5 mm	7 mm	5 mm	7 mm
Teeth with uncleaned fins	2	1	2	2
Oval canals	7	8	7	8
“Risk zones” (canal wall ≤1 mm thick)	3	2	3	2
Perforation	1	0	1	0

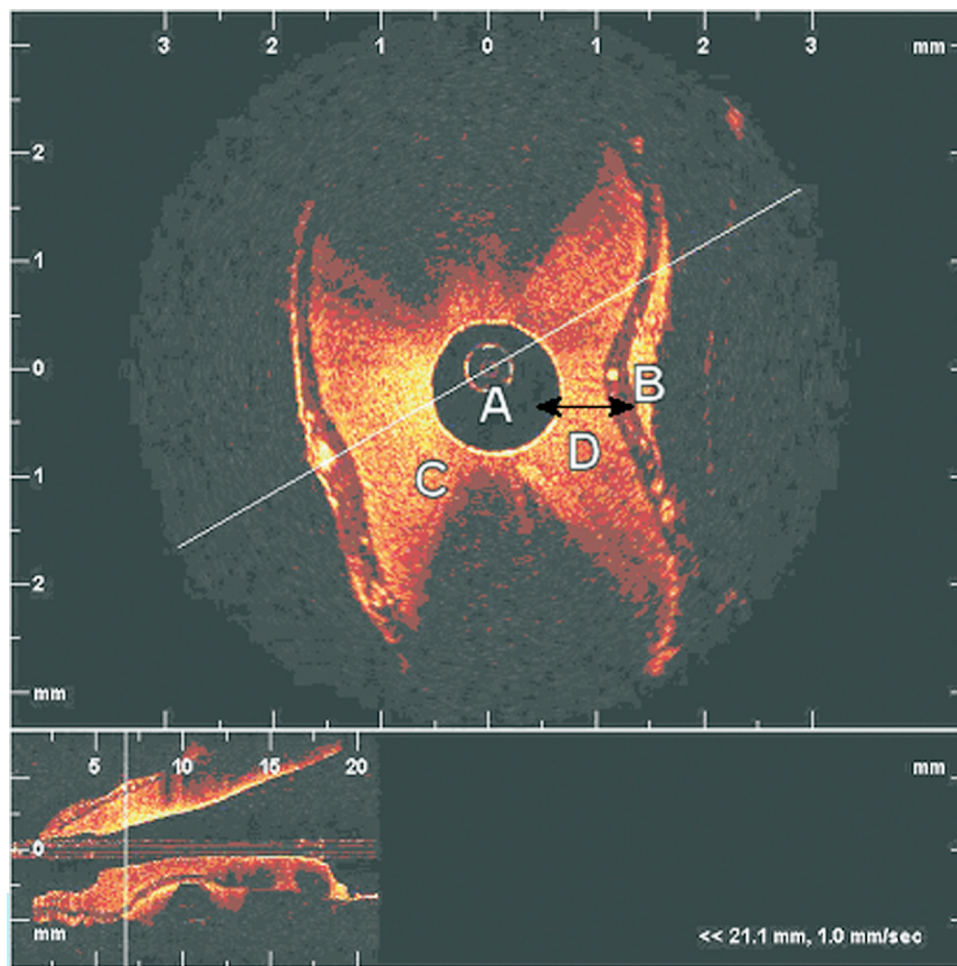


Figure 3. The OCT output at 7 mm from the apex shows a cross-section of a prepared canal. (A) The root canal, (B) cementum, and (C) dentinal tubules. (D) “Risk zone” (canal wall = 1-mm thick).

have a pixel size approaching $100\ \mu\text{m}$. Second, the probe size is usually much bigger than a root canal. These methods are also time consuming and often require the interpretation of thousands of images. In contrast, OCT combines a very narrow optical fiber measuring 0.5 mm in diameter, with high-resolution capacities, enabling imaging of objects measuring a few micrometers and does not involve ionizing radiation. The imaging wire can be deployed independently or integrated straightforwardly into existing therapeutic or imaging catheters. Furthermore, it can easily fit into a prepared root canal and is flexible, allowing penetration through curvatures. The optical probe rotates inside the imaged vessel so that adjacent lines in each rotation compose a frame showing a cross-section of the tissue architecture in the wall. The scan is quick and takes 15 seconds for a 15-mm long root.

The influence of a specific tissue’s microstructure on light propagation is an important factor when considering diagnostic applications of light. Dentin is a structure with anisotropic optical properties that is different from most other biological tissues (19) because the tubules are the primary cause of light scattering (20). In our experiments, the root dentin was semitransparent, allowing imaging of the outer root surface as well. However, a thicker dentine wall will not allow sufficient light penetration, and the outer outline of the root will not be seen. However, some care has to be taken with interpreting measured distances in the OCT images of dentin. The OCT system assumes a refractive index of the imaging medium that is close to that of water (1.33), which is a reasonable approximation for soft tissues. Dental and bone-like

materials have a higher index of refraction, closer to 1.5 (20). As a result, the distances inside the tooth are approximately 13% shorter than suggested by the images. Straightforward image processing can remove this ambiguity. The tooth was placed in a water bath to improve the refractive index match between imaging medium and dental material. A contrast in refractive index causes light to be reflected from the interface (21), reducing the signal from the tissue. A smaller refractive index step (achieved by imaging through water, instead of air) leads to a smaller reflection at the dentin interface and improves image quality. Furthermore, because clinical application of the OCT system was also considered, placing the optical fibre in a wet canal is more clinically relevant. Indeed, one of the big disadvantages of the recently introduced “endoscope” to endodontic clinical practice (22) is that it requires a dry environment. The endoscope has a 0.7-mm probe that is inserted into a dry canal to image the inner anatomy. However, this system is based on a camera that produces a digital image and not on microscopic-level characterization or light propagation as observed by the OCT. Furthermore, no penetration of light through the dentinal tubuli is possible and, hence, no detection of the outer outline of the root. The smaller diameter and increased flexibility of the OCT probe allows deeper penetration and easier application in clinical situations.

It is noteworthy that the current experimental setting requires the catheter to penetrate through the apex, pulling it back through the canal. Adaptation of the catheter to allow imaging from the fiber’s tip is possible, which will enable imaging without probing through the apex and thus allow

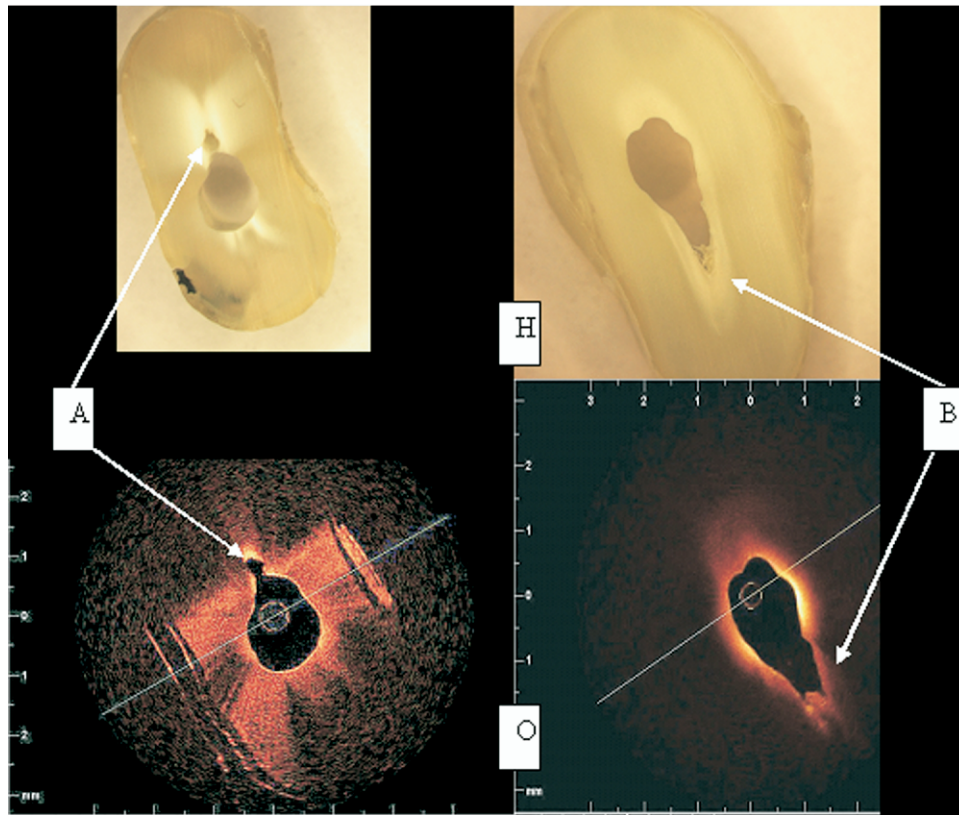


Figure 4. Oval canals and uncleared fins at 7 mm from the apex revealed by histology (H) and OCT (O): sample A and sample B.

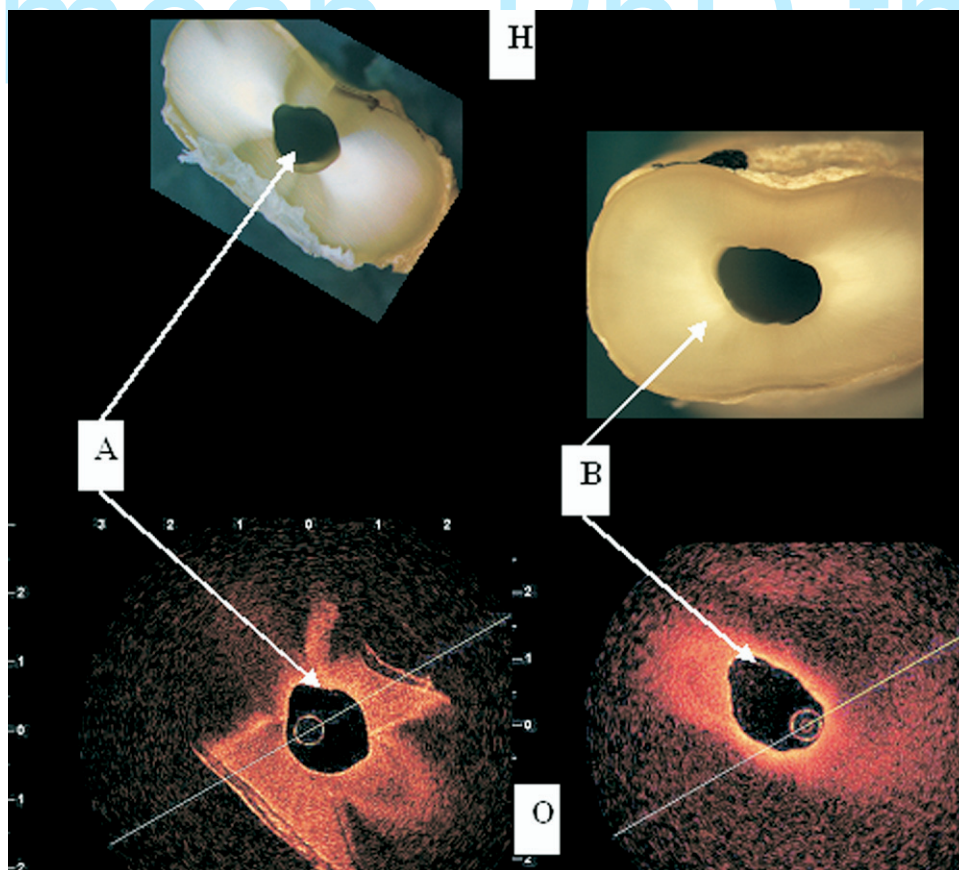


Figure 5. Cleaned root canals at 7 mm from the apex revealed by histology (H) and OCT (O): sample A and sample B.

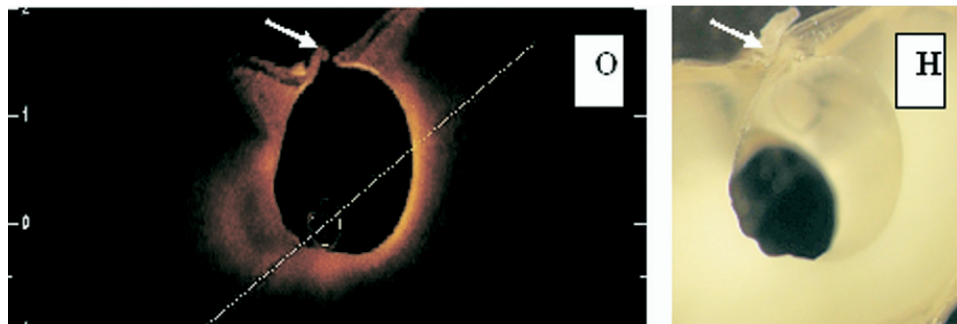


Figure 6. Canal perforation during preparation at 5 mm from the apex revealed by histology (H) and OCT (O).

clinical imaging all the way to the apical part. Another disadvantage of the current setting is the cost of the OCT catheter. Because these wires are designed for disposable cardiac use, they are relatively expensive. Nonetheless, OCT imaging systems for clinical dental use are under development, and more affordable versions could be available soon.

In conclusion, this study shows a noninvasive and nondestructive technique for analyzing the anatomy and cleanliness of root canal walls. OCT could generate intracanal microscopic images without applying ionizing radiation and could be used *in vivo*.

References

1. Wu MK, R'oris A, Barkis D, Wesselink PR. Prevalence and extent of long oval canals in the apical third. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2000;89:739–43.
2. Mauger MJ, Schindler WG, Walker WA 3rd. An evaluation of canal morphology at different levels of root resection in mandibular incisors. *J Endod* 1998;24:607–9.
3. Tamse A, Katz A, Pilo R. Furcation groove of buccal root of maxillary first premolars—a morphometric study. *J Endod* 2000;26:359–63.
4. Huang D, Swanson EA, Lin CP, et al. Optical coherence tomography. *Science* 1991;254:1178–81.
5. Regar E, van Beusekom HM, van der Giessen WJ, Serruys PW. Images in cardiovascular medicine. Optical coherence tomography findings at 5-year follow-up after coronary stent implantation. *Circulation* 2005;112:345–6.
6. Pitris C, Jesser C, Boppart SA, et al. Feasibility of optical coherence tomography for high-resolution imaging of human gastrointestinal tract malignancies. *J Gastroenterol* 2000;35:87–92.
7. Gambichler T, Hyun J, Moussa G, et al. Optical coherence tomography of cutaneous lupus erythematosus correlates with histopathology. *Lupus* 2007;16:35–8.
8. Low AF, Tearney GJ, Bouma BE, Jang IK. Technology insight: optical coherence tomography—current status and future development. *Nat Clin Pract Cardiovasc Med* 2006;3:154–62.
9. Schmitt JM. Optical coherence tomography (OCT): a review. *IEEE J Sel Top Quantum Electron* 1999;5:1205–15.
10. Colston BW Jr, Everett MJ, Sathyam US, DaSilva LB, Otis LL. Imaging of the oral cavity using optical coherence tomography. *Monogr Oral Sci* 2000;17:32–55.
11. Otis LL, Everett MJ, Sathyam US, Colston BW Jr. Optical coherence tomography: a new imaging technology for dentistry. *J Am Dent Assoc* 2000;131:511–4.
12. Amaechi BT, Higham SM, Podoleanu AG, Rogers JA, Jackson DA. Use of optical coherence tomography for assessment of dental caries: quantitative procedure. *J Oral Rehabil* 2001;28:1092–3.
13. Baumgartner A, Dichtl S, Hitzberger CK, et al. Polarization-sensitive optical coherence tomography of dental structures. *Caries Res* 2000;34:59–69.
14. Velvart P, Hecker H, Tillinger G. Detection of the apical lesion and the mandibular canal in conventional radiography and computed tomography. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2001;92:682–8.
15. Eder A, Kantor M, Nell A, et al. Root canal system in the mesiobuccal root of the maxillary first molar: an *in vitro* comparison study of computed tomography and histology. *Dentomaxillofac Radiol* 2006;35:175–7.
16. Youssefzadeh S, Gahleitner A, Dorffner R, Bernhart T, Kainberger FM. Dental vertical root fractures: value of CT in detection. *Radiology* 1999;210:545–9.
17. Plotino G, Grande NM, Pecci R, Bedini R, Pameijer CH, Somma F. Three-dimensional imaging using microcomputed tomography for studying tooth macromorphology. *J Am Dent Assoc* 2006;137:1555–61.
18. Jung M, Lommel D, Klimek J. The imaging of root canal obturation using micro-CT. *Int Endod J* 2005;38:617–26.
19. Kienle A, Forster FK, Diebold R, Hibst R. Light propagation in dentin: influence of microstructure on anisotropy. *Phys Med Biol* 2003;48:N7–14.
20. Zijp JR, ten Bosch JJ. Theoretical model for the scattering of light by dentin and comparison with measurements. *Appl Opt* 1993;32:411–36.
21. Born M, Wolf E. *Principles of Optics*. Ed 7. Cambridge, UK: Cambridge University Press; 2002:132–4.
22. Bahcall JK, Barss JT. Fiberoptic endoscope usage for intracanal visualization. *J Endod* 2001;27:128–9.