Optical approach to the periodontal ligament under orthodontic tooth movement: A preliminary study with optical coherence tomography

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Introduction: Optical coherence tomography (OCT) is a diagnostic tool that can make near-histologic tomographic images without a biohazard. Due to its high resolution (average, 4 μm) and safety (using light as the source), it has been applied widely in medical fields to replace invasive biopsies. But the trials in dentistry have been restricted to mainly detecting dental caries and oral cancer. In this preliminary study for successive human studies, we tried to evaluate whether OCT can be helpful in determining tooth movement under light orthodontic forces. **Methods:** Orthodontic distraction forces (0, 5, and 10 g) were applied to the mandibular incisors of 6 white rats (10 weeks old) for 5 days by using individualized loop springs (round Elgiloy, 0.018-in diameter, Rocky Mountain Orthodontics, Denver, Colo). The changed periodontal ligaments were imaged with OCT and digital intraoral radiography 2 dimensionally. Both tensile and compressive ligaments were measured and compared. **Results:** With OCT images, we could measure changed ligaments from all directions; radiography could not show the portions overlapped by teeth. The averages of measured ligament width in OCT were larger than those from radiography in all groups. **Conclusions:** This preliminary study shows the possible evaluation and prediction of precise tooth responses under orthodontic forces by using real-time OCT. (Am J Orthod Dentofacial Orthop 2009;135:252-9)

Orthodontic treatment always needs careful biomechanical considerations to prevent side effects such as root resorption, decalcification, and periodontal problems that can cause irreversible bone destruction.[1-3] Although conventional radiography is a popular diagnostic aid in clinical dentistry, it gives us only overlapped 2-dimensional (2D) images that can confuse diagnosis.[4-7] Computed tomography (CT) can be another solution, but it also has a problem: exposure to radiation, especially in specific groups including pregnant women, although CT has been improved to address this problem.[8]

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Optical coherence tomography (OCT) is a noninvasive medical diagnostic imaging modality with a high resolution (average, 4 μm) that can give near-histologic images with a safe broadband light source.[9,10] Broadband laser light waves are emitted from a source and directed toward a beam splitter. One wave is sent toward a reference mirror with a known path length and the other toward the tissue sample. After the 2 beams reflect off the reference mirror and the tissue surfaces at varying depths in the sample, the reflected light is directed back toward the beam splitter, where the waves are recombined and read with a photo detector (Fig 1). The basic principle of OCT is analogous to CT (which uses x-rays), magnetic resonance imaging (which uses spin resonance), and B-scan ultrasound (which uses sound waves). But OCT uses only light to derive its image in a noncontact, noninvasive system.[11] Because OCT has near-infrared wavelength (about 840 nm), the examination causes minimal discomfort for the patient.[12] It has been used in various medical fields including ophthalmology,[13] gastroenterology,[14] urology,[15] gynecology,[16] and dentistry.[17-20] Its high-resolution and noninvasive character is also useful for early diagnosis of cancers.[21] Its other advantage is that it can be used with low-priced compact equipment; this is useful for chair-side approaches for real-time evaluation of patients.

The periodontal ligament (PDL) plays an important role in the function of teeth with its specified recep-

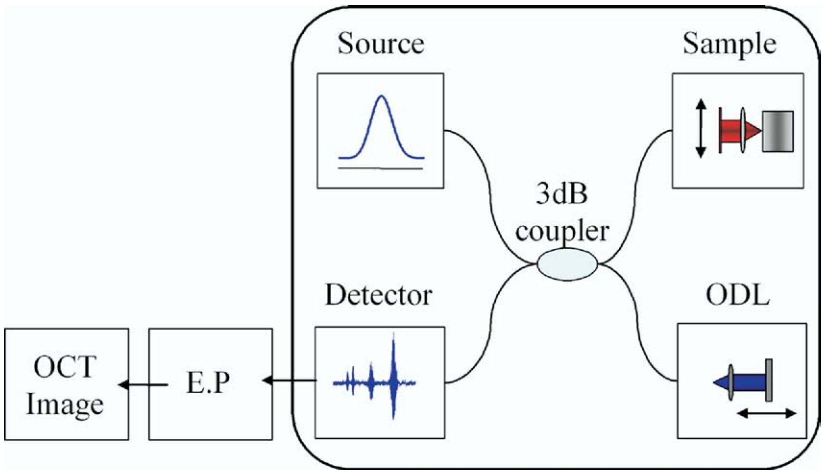

Fig 1. Schematic image of OCT system: *ODL,* optical delay line; *E.P,* electrical processing. At first, the light source is split into the sample and the ODL by using the coupler. Then the detector detects interferences between signals from the ODL and the sample when reflected light from the sample and the ODL are recombined. Finally, electrical processing changes these interferences into visible optical images.

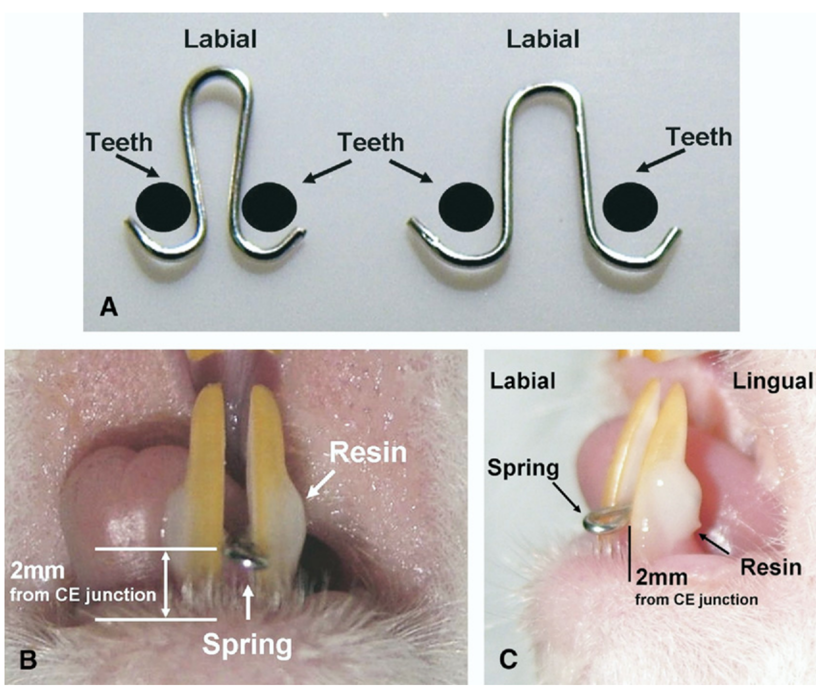

Fig 2. Force application. **A,** Elgiloy springs before preactivation: springs for 5 (*left*) and 10 (*right*) g of force. Lateral curvature at both ends of spring reinforces retention on tooth surfaces. **B,** Applied spring, frontal view. The spring was positioned 2 mm above the cementoenamel junction. **C,** Applied spring, lateral view.

tors[22] and is also the site where the sequential cycle of tooth movement starts during orthodontic treatment.[23] The study of tooth function involves bioelastic phenomena and the consideration of compressive and tensile forces that exceed, in duration and magnitude, the bioelastic limit to induce bioplastic transformation or exceed the ultimate strength of biologic materials with biodisruptive deformation of tissues. The first phase of each tooth function takes place through the PDL space.[24] Although there have been many studies about the PDL, its role around teeth is not completely understood yet. It inhibits closure of the jaws via a reflex pathway when a predetermined pressure on the teeth has been exceeded by using mechano-receptors, controls the movements of the maxilla during mastication with a complex regulatory system,[25] and cushions outer stresses on teeth including orthodontic and parafunctional forces. If we can identify early responses of the PDL under stress, we can do precise differential diagnoses of various undesirable intraoral situations—eg, teeth affected by bruxism, uneven load distributions on abutment teeth, occlusal interferences on teeth, and initial tooth responses under orthodontic forces.

This preliminary study was done before any human studies were undertaken, with the hypothesis that each tooth response under orthodontic forces can be predicted precisely by analyzing tomographically the change of the PDL in both compressive and tensile sites tomographically. To verify the feasibility of OCT for PDL evaluation, several light orthodontic forces (0, 5, and 10 g) were applied on the mandibular incisors of rats (10 weeks old). A homemade OCT system (time-domain OCT system, Gwangju Institute of Science and Technology, Gwangju, Korea) was used for OCT imaging. Intraoral digital radiography (digital X-ray intraoral sensor system, Vatech, Seoul, Korea) gave us the baseline for comparison. The PDL widths were measured and compared after imaging.

MATERIAL AND METHODS

The time-domain OCT system was implemented with a fiber-based Michelson interferometer to evaluate the PDL (Fig 1). It used a broadband light source having an output power of 4 mW. The center wavelength was $\lambda_c = 1310$ nm, and the bandwidth was $\Delta\lambda = 58$ nm. For an OCT image, the detected signal from the fiber-based interferometer was band-pass filtered, demodulated electronically, sampled by a data acquisition board, and finally constructed into a 2D or 3-dimensional (3D) image with a personal computer. The axial and lateral resolutions were measured at 14 and 10 μm in this study, respectively; this might be enough to detect the changes in the PDL (average, 0.15 mm width in rats) precisely.

Six 10-week-old white male rats (Sprague Dawley) were selected. The periodontal tissue of the rat is active because the incisors erupt approximately 10 μm per hour, so it is adequate for a sensitive PDL response model.[26] In addition, all rats were in their active growing period at 10 weeks, so the level of their adaptation to foreign appliances was so high that the failure rate during the experiment was reduced.

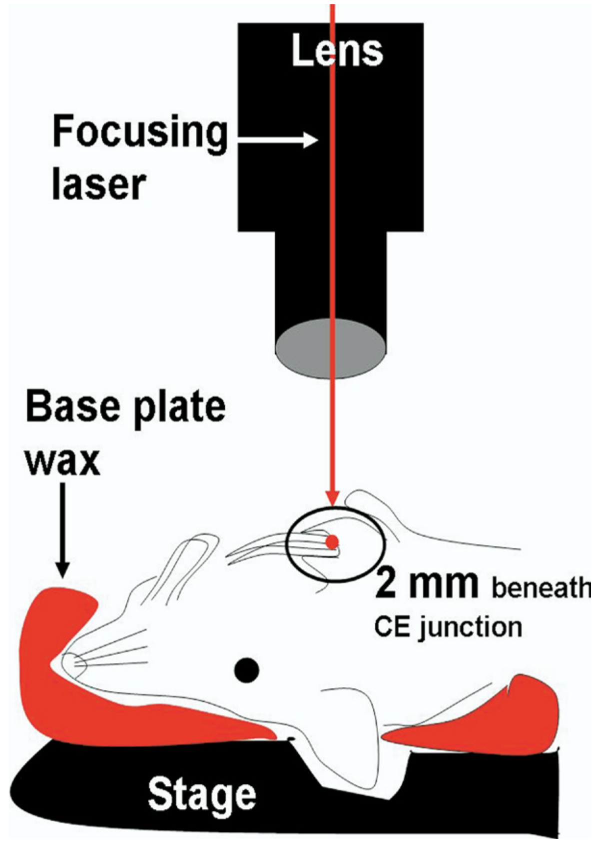

Fig 3. Schematic image. The rat's head was set on the imaging stage with individualized base plate wax holder under general anesthesia. The base plate wax holder maintained the gingival surface in the target area at a right angle to the beam during imaging. The focus of the imaging was set at 2 mm beneath the cementoenamel junction.

Various levels (0, 5, and 10 g) of light distractional orthodontic forces were applied on the mandibular incisors of 6 rats. These force ranges were selected on the basis of a previous study.[24] Every two rats were used for each force level of the individualized 0.018-in round Elgiloy (RMO, Denver, Colo) loop spring. After preactivation to control forces, the springs were heat-treated to ensure light continuous forces during the experiments (Fig 2, *A*).

All nonsurgical processes in this study were done under the guidance of the institutional animal care and use committee at Ulsan University (Ulsan, South Korea). General anesthesia was achieved by injection of tribromo-ethanol (2,3,4-tribromo-ethanol, 300 mg per kilogram) intramuscularly after ether inhalation. Then prepared springs were placed between the mandibular

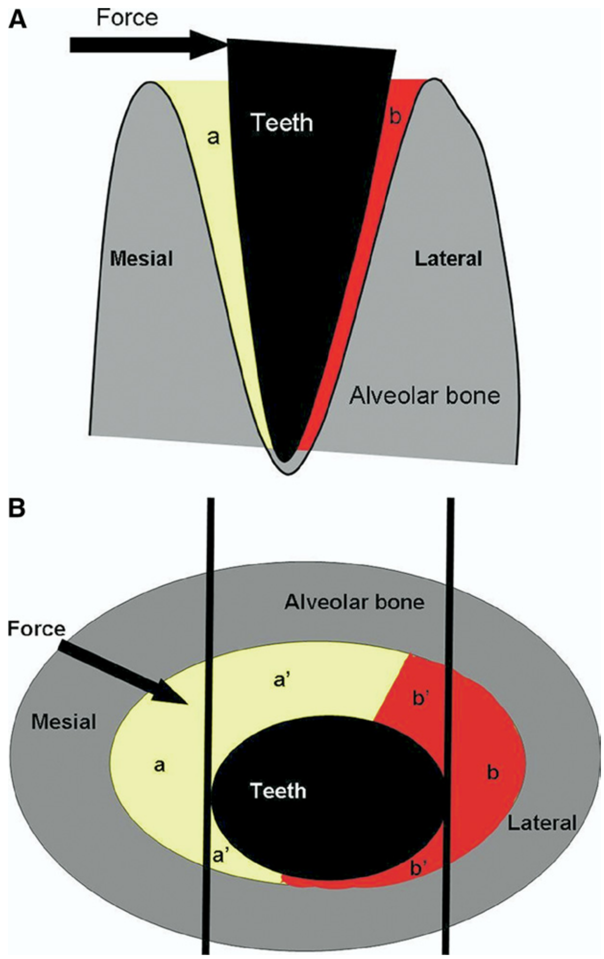

Fig 4. Schematic images of measurement. **A,** Radiography: *a,* tensile side; *b,* compressive side. **B,** OCT image cross-section view: *a* and *a′,* tensile side; *b* and *b′*, compressive side. In radiography, a′ and b′ areas cannot be evaluated because of overlapping teeth (*black-line* bounded area overlapped by teeth). The tensile (*a* and *a′*) and compressive (*b* and *b′*) sides were divided by the perpendicular line to the force direction at the center of the teeth. Each of the 20 areas in both extended and compressed ligaments was measured for comparison.

incisors. To reinforce retention, light-cured resin (Light Bond, Reliance Orthodontic Products, Itasca, Ill) was added over both ends of the spring after sequential processes including tooth-surface cleaning with pumice and a microbrush connected to a low-speed micro-engine, acid etching (37% phosphoric acid) on lateral surfaces of the mandibular incisors for 15 seconds, washing with saline solution for 10 seconds, and complete drying with dehydrated air. The lateral ends of the springs were positioned 2 mm above the cementoenamel junction to prevent spring distortion by rapid tooth eruption or irritation during mastication (Fig 2, *B* and *C*). Each rat was kept in an individual cage for 5 days. Routine checks for daily food consumption and spring retention were done every day to reduce the animals' discomfort and maintain the stability of the applied forces.

After 5 days, OCT imaging evaluated the PDLs around the mandibular incisors of each rat. To compare with the results from intraoral digital X-ray radiography, 2D OCT images were acquired instead of 3D ones. The target area for imaging was the PDL and the ligament space at 2 mm beneath the cementoenamel junction, which is the easiest area to be examined with OCT in a real clinical situation and can show the most critical responses of the PDL in the cervical area under orthodontic forces. The head of each rat was held on the stage with base plate wax mold. The focusing laser, used for visible focusing because the light source is invisible, was set at 2 mm beneath the cementoenamel

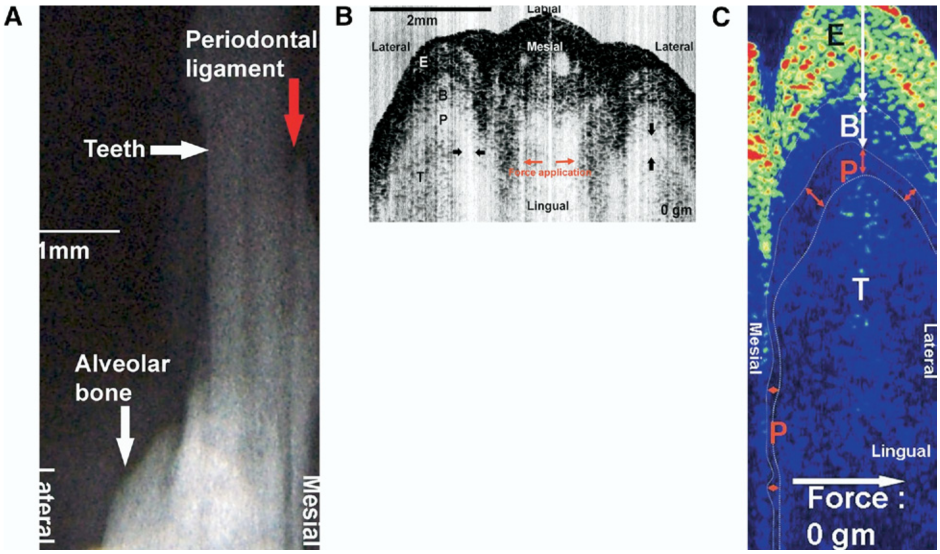

Fig 5. Images of a PDL at 0 g. **A,** Radiograph. **B,** OCT; distractional force was applied (*red arrows*) laterally in other groups. **C,** Logging OCT images; the boundary of each tissue can be identified more clearly.

junction at a right angle (Fig 3). The lower lip was retracted during imaging with a homemade wire hook (0.7 mm in diameter, round stainless steel, G&H Wire Company, Greenwood, Ind) connected on the stage.

Intraoral radiography evaluated the same area for comparison before each OCT imaging.

The width of the PDL in both radiography and OCT images was measured and compared. Every 20 points were selected in tensile and compressive regions for this measurement. PDLs in only the mesial and lateral portions around teeth could be measured in radiography (*a* and *b* in Fig 4, *A* and *B*), although the widths were measured from all directions in the OCT images (Fig 4, *B*). In OCT image, the areas opposite to the force (the perpendicular line to the force at the center of the tooth divided these 2 areas) were regarded as the compressive ligament areas (*b* and *b′* in Fig 4, *B*).

RESULTS

In intraoral radiography, enlarged PDL spaces can be identified with magnified radiographic images. But only the mesial and lateral portions of the PDL could be measured because of the portion overlapped by teeth (*a′* and *b′* in Figs 4; 5, *A*; 6, *A*; and 7, *A*). The same teeth were also evaluated with OCT. It showed more precise tomographic images of PDLs and dynamic mechanical changes according to different forces (Figs 5, *B*; 6, *B*; and 7, *B*). After data logging, an OCT image can be converted into a more visible one for easier diagnosis for clinicians (Figs 5, *C*; 6, *C*; and 7, *C*). The same color in logging images showed tissues with the same optical properties. The precise figures of the compressive and tensile PDL could be traced by using these images. Solid images of the ligament between the alveolar bone and the teeth in OCT showed active responses of the PDL under orthodontic forces from many directions, not only the lateral gaps shown in radiography. In addition, the outer soft tissue including the epithelium, which is difficult to distinguish in radiography, was defined clearly in the OCT images (Fig 5, *B*).

The measured widths were compared (Table). Although radiography and OCT showed similar tendencies of PDL widths according to the force increase, OCT showed larger measurements in both compressive and tensile sites (Table, Fig 8). In the case of OCT, the differences between maximum and minimum measurements were also larger than those of radiography (Fig 9). The standard deviations in measured ligament widths also were larger in OCT than with radiography, except the tensile side at 5 g of force (Table).

To reduce errors, an inspector (J.H.B.) measured all widths 3 times with a week between each measurement. All data were analyzed with statistical software (SPSS for Windows, version 13.0, SPSS, Chicago, Ill).

DISCUSSION

Most previous studies about dental applications of OCT have been related to dental caries,[27] periodontal disease,[14] and oral cancer.[28,29] No trials have evaluated

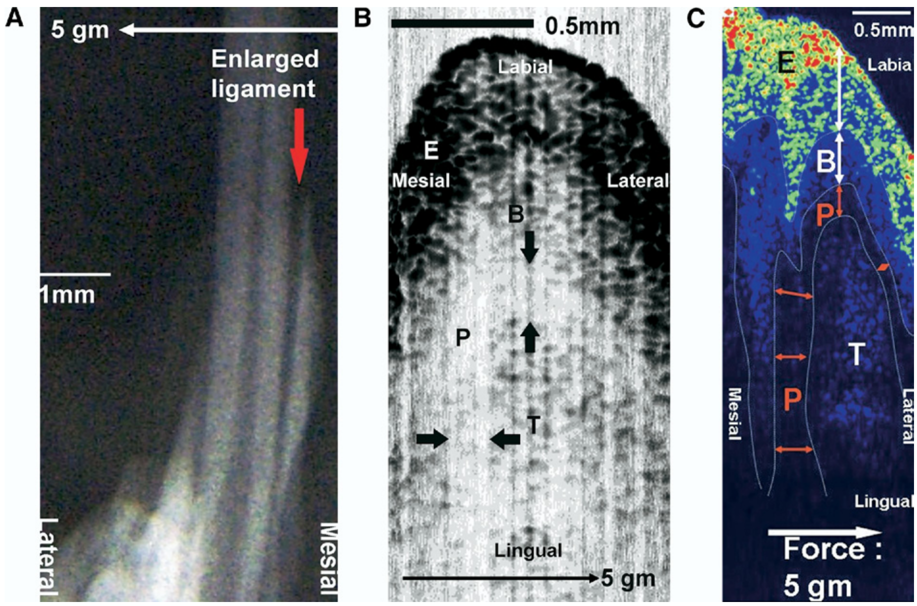

Fig 6. Images of a PDL at 5 g. **A,** Radiograph; *white arrow* shows direction of force. **B,** OCT; more enlarged ligament space can be identified (between *black arrows*). **C,** Logging OCT; dynamic figures of ligament can be seen (*red arrows*).

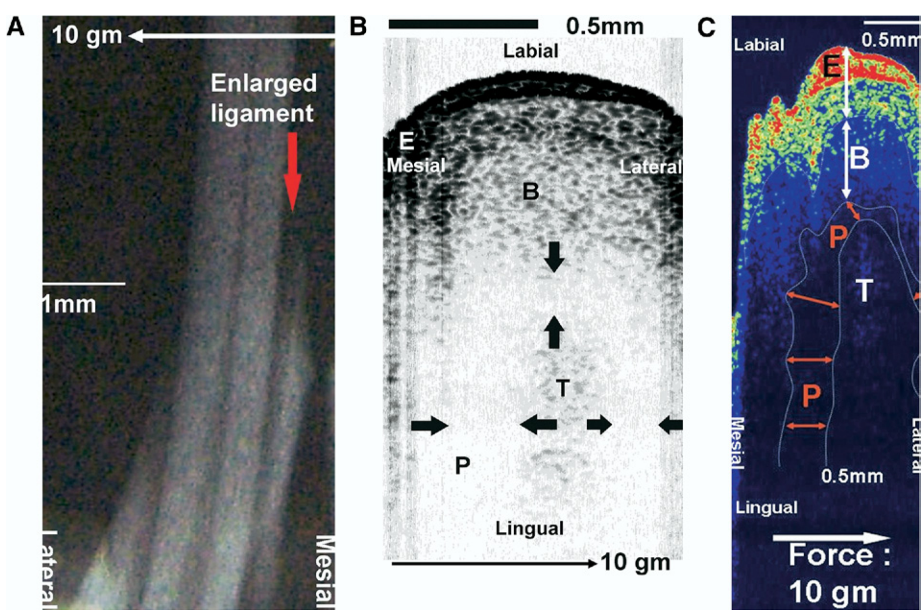

Fig 7. Images of a PDL at 10 g. **A,** Radiograph. **B,** OCT image. **C,** Logging OCT image; near-histologic images can be identified. According to increased forces, enlarged PDL spaces (*red arrows*) were seen, and multidirectional evaluations of PDL changes were possible on tomographic images (*E,* epithelium; *B,* alveolar bone; *P,* PDL; *T,* teeth).

active responses of the PDL with optical devices. In this study, we could evaluate dynamic changes in the PDL using OCT (Figs 5-7). We concluded that several factors must be considered before real clinical applications of OCT for PDL evaluation on the basis of this experiment.

Generally, the average effective penetrating depth of OCT is only 3 mm.[30] Thus, OCT cannot be used to

Table. Measurements of the changes in the PDL

	0 g		5 g		10 g	
Measurement (mm)	*Compressive*	*Tensile**	*Compressive*	*Tensile*	*Compressive*	*Tensile*
Radiography (average ± SD)	0.054 ± 0.014	0.072 ± 0.013	0.053 ± 0.004	0.140 ± 0.039	0.004 ± 0.001	0.158 ± 0.053
OCT (average ± SD)	0.087 ± 0.022	0.090 ± 0.063	0.121 ± 0.029	0.173 ± 0.030	0.107 ± 0.036	0.326 ± 0.115
Radiography (maximum/ minimum)†	0.085/0.029	0.100/0.053	0.062/0.049	0.205/0.062	0.007/0.002	0.268/0.098
OCT (maximum/minimum)†	0.136/0.063	0.188/0.030	0.276/0.097	0.487/0.103	0.227/0.067	0.570/0.197

*There is no extended area under 0 g of force practically, but the mesial area was described as "tensile" to be consistent with other groups.
†Maximum and minimum measurements in each area.

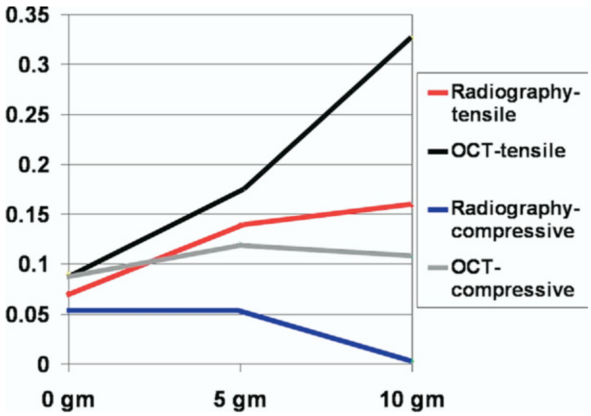

Fig 8. Changes in PDL. OCT showed larger measurements in both compressive and tensile PDL than those from radiographic images.

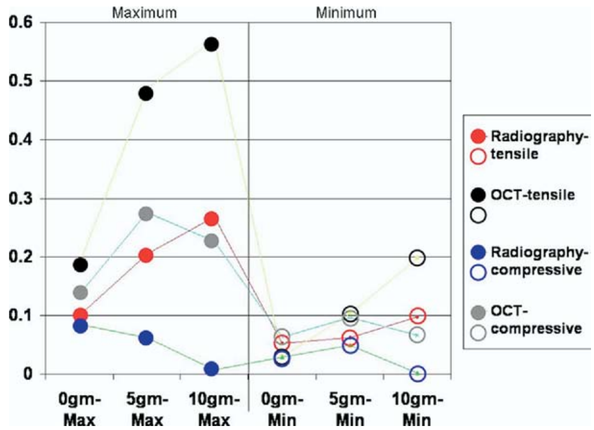

Fig 9. Maximum and minimum measurements in each group. OCT showed larger difference between maximum and minimum measurements in each group than radiography because tomographic OCT images included more changes in the PDL.

evaluate the PDL far from the cervical area where the overlying tissue is thick. To keep the rats' heads stable during imaging, we did not use a hand-held probe in this experiment. But a hand-held probe can be helpful for increasing the effective penetrating depth in human studies by placing the probe on the target area. The diameter of the OCT probe can be reduced to 1.2 mm, which is enough to be used in real intraoral applications.[31] In this study, we could get dissected images of root up to two-thirds of its length with the 3-mm average effective penetrating depth.

OCT can support near-histologic images with high resolution (average, 4 μm). We used 10-μm resolution for this study; this is enough to evaluate precise changes of the PDL, and the results were similar to the usual histologic sample images of periodontal tissues (Figs 5, *C*; 6, *C*; and 7, *C*). Radiography can resolve an average of 10 line pairs per millimeter, which is far from histologic images.[32,33]

In the prediction of tooth movement, conventional radiography shows only overlapped images. Thus, we could not evaluate the changes of the PDL in areas overlapped by teeth (*a′* and *b′* in Fig 4, *B*). But OCT could support tomographic images with more dynamic structures of the PDL (Fig 5, *C*; 6, *C*; and 7, *C*). These dynamic structures gave us more measurements in each portion of the ligament than those from radiography. By differentiating the information of areas overlapped by teeth, which radiography usually cannot detect, OCT showed a wide variety of measurements in each group (Table, Figs 8 and 9).

Thus, OCT can predict tooth movements more precisely in clinical situations. In this experiment, we could determine tooth movements in multiple directions—eg, mesiolingual and mesiobuccal—by evaluating the 3D distribution of the tensile and compressive ligaments in OCT images. But we could determine only 2D tooth movement—eg, mesial or lateral—with intraoral radiography.

In comparison with radiography, OCT is convenient and has no biohazard. It can be used at chair-side without protective equipment and for any patient, including infants and pregnant women.

In addition, an OCT image can be evaluated in real time. Although it requires another processing with 3D imaging software (Amira, Mercury Computer System, Carlsbad, Calif), OCT images can be converted into 3D ones like CT images.

Just like other many diagnostic devices, OCT is not a perfect diagnostic device by itself. But we figured out its possibilities in the determination of tooth response and changes in periodontal tissue during orthodontic treatment. Our next step is to compare micro-CT images and 3D OCT for PDL areas on the basis of this study.

CONCLUSIONS

By using a time-domain OCT system, early responses of the PDL under light continuous orthodontic forces were evaluated preliminarily. More precise and solid images of PDLs were acquired by this tomographic system, and active determination of the minute changes of the PDL under orthodontic forces was possible by using multi-directional evaluations that are impossible with conventional intraoral radiography.

Our results suggest possible applications of optical imaging for predicting tooth movements precisely and preventing side effects in the early stages of orthodontic treatment.

REFERENCES

1. Owman-Moll P. Orthodontic tooth movement and root resorption with special reference to force magnitude and duration. A clinical and histological investigation in adolescents. Swed Dent J Suppl 1995;105:1-45.
2. Thilander BL. Complications of orthodontic treatment. Curr Opin Dent 1992;2:28-37.
3. Wennstrom JL, Lindhe J, Sinclair F, Thilander B. Some periodontal tissue reactions to orthodontic tooth movement in monkeys. J Clin Periodontol 1987;14:121-9.
4. Youssefzadeh S, Gahleitner A, Dorffner R, Bernhart T, Kainberger FM. Dental vertical root fractures: value of CT in detection. Radiology 1999;210:545-9.
5. van der Stelt PF. Modern radiographic methods in the diagnosis of periodontal disease. Adv Dent Res 1993;7:158-62.
6. Ito K, Yoshinuma N, Goke E, Arai Y, Shinoda K. Clinical application of a new compact computed tomography system for evaluating the outcome of regenerative therapy: a case report. J Periodontol 2001;72:696-702.
7. Gröndahl HG, Huumonen S. Radiographic manifestations of periapical inflammatory lesions. Endodontic Topics 2004;8:55-67.
8. Lowe SA. Diagnostic radiography in pregnancy: risks and reality. Aust N Z J Obstet Gynaecol 2004;44:191-6.
9. Huang D, Swanson EA, Lin CP, Schuman JS, Stinson WG, Chang W, et al. Optical coherence tomography. Science 1991; 254:1178-81.
10. Podoleanu AG, Rogers JA, Jackson DA, Dunne S. Three dimensional OCT images from retina and skin. Opt Express 2000;7:292-8.
11. Schuman JS, Hee MR, Arya AV, Pedut-Kloizman T, Puliafito CA, Fujimoto JG, et al. Optical coherence tomography: a new tool for glaucoma diagnosis. Curr Opin Ophthalmol 1995;6:89-95.
12. Ripandelli G, Coppé AM, Capaldo A, Stirpe M. Optical coherence tomography. Semin Ophthalmol 1998;13:199-202.
13. van Velthoven ME, Faber DJ, Verbraak FD, van Leeuwen TG, de Smet MD. Recent developments in optical coherence tomography for imaging the retina. Prog Retin Eye Res 2007;26:57-77.
14. Fujimoto JG. Optical coherence tomography for ultrahigh resolution in vivo imaging. Nat Biotechnol 2003;21:1361-7.
15. Tearney GJ, Brezinski ME, Southern JF, Bouma BE, Boppart SA, Fujimoto JG. Optical biopsy in human urologic tissue using optical coherence tomography. J Urol 1997;157:1915-9.
16. Feldchtein FI, Gelikonov GV, Gelikonov VM, Kuranov RV, Sergeev AM, Gladkova ND, et al. Endoscopic applications of optical coherence tomography. Opt Express 1998;3:257-70.
17. Colston BW Jr, Sathyam US, DaSilva LB, Everett MJ, Stroeve P, Otis LL. Dental OCT. Opt Express 1998;6:230-8.
18. Feldchtein FI, Gelikonov GV, Gelikonov VM, Iksanov RR, Kuranov RV, Sergeev AM, et al. In vivo OCT imaging of hard and soft tissue of the oral cavity. Opt Express 1998;6:239-50.
19. Wang XJ, Milner TE, de Boer JF, Zhang Y, Pashley DH, Nelson JS. Characterization of dentin and enamel by use of optical coherence tomography. Appl Opt 1999;38:2092-6.
20. 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.
21. Yasuda K. Early gastric cancer: diagnosis, treatment techniques and outcomes. Eur J Gastroenterol Hepatol 2006;18:839-45.
22. Jacobs R, van Steenberghe D. Role of periodontal ligament receptors in the tactile function of teeth: a review. J Periodontal Res 1994;29:153-67.
23. Melsen B. Tissue reaction to orthodontic tooth movement—a new paradigm. Eur J Orthod 2001;23:671-81.
24. Storey E. The nature of tooth movement. Am J Orthod 1973;63: 292-314.
25. Kloprogge MJ. Reflex control of the jaw muscles by stimuli from receptors in the periodontal membrane. J Oral Rehabil 1975;2: 259-72.
26. Brun-Murdoch RA. The effect of applied forces on the eruption of rat maxillary incisor. Arch Oral Biol 1981;26:939-43.
27. Fried D, Featherstone JD, Darling CL, Jones RS, Ngaotheppitak P, Buhler CM. Early caries imaging and monitoring with near-infrared light. Dent Clin North Am 2005;49:771-93.
28. Chen SF, Lu CW, Tsai MT, Wang YM, Yang C, Chiang CP. Oral cancer diagnosis with optical coherence tomography. Conf Proc IEEE Eng Med Biol Soc 2005;7:7227-9.
29. Wilder-Smith P, Krasieva T, Jung WG, Zhang J, Chen Z, Osann K, et al. Noninvasive imaging of oral premalignancy and malignancy. J Biomed Opt 2005;10:051601.
30. Pan Y, Lavelle JP, Bastacky SI, Meyers S, Pirtskhalaishvili G, Zeidel ML, et al. Detection of tumorigenesis in rat bladders with optical coherence tomography. Med Phys 2001;28:2432-40.
31. Wirbelauer C, Scholz C, Hoerauf H, Pham DT, Laqua H, Birngruber R. Noncontact corneal pachymetry with slit lamp-adapted optical coherence tomography. Am J Ophthalmol 2002; 133:444-50.
32. Singhal V, Strassler HE. Digital radiography for the allied dental professional. Contemp Dent Assisting 2007;Jan/Feb:1-9.
33. Haring J, Howarten L. Dental radiography. Principles and techniques. 3rd ed. Philadelphia: Elsevier; 2006.