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

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-
tors and is also the site where the sequential cycle of tooth movement starts during orthodontic treatment. 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

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.
phase of each tooth function takes place through the
PDL space. 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, and cushions outer
stresses on teeth including orthodontic and para-
functional forces. If we can identify early responses of
the PDL under stress, we can do precise differential
diagnoses of various undesirable intraoral situations—
e.g., 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 pre-
dicted 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 wave-
length was λc = 1310 nm, and the bandwidth was Δλ
= 58 nm. For an OCT image, the detected signal from
the fiber-based interferometer was band-pass filtered,
demodulated electronically, sampled by a data acquisi-
tion board, and finally constructed into a 2D or 3-di-
imensional (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. 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.

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. 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 Ko-
rea). 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
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 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.
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, periodontal disease, and oral cancer. No trials have evaluated...
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. Thus, OCT cannot be used to
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.\textsuperscript{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.\textsuperscript{31}

OCT can support near-histologic images with high resolution (average, 4 $\mu$m). We used 10-$\mu$m 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.\textsuperscript{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.

**Table.** Measurements of the changes in the PDL

<table>
<thead>
<tr>
<th>Measurement (mm)</th>
<th>$0 \text{ g}$</th>
<th></th>
<th>$5 \text{ g}$</th>
<th></th>
<th>$10 \text{ g}$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compressive</td>
<td>Tensile*</td>
<td>Compressive</td>
<td>Tensile</td>
<td>Compressive</td>
<td>Tensile</td>
</tr>
<tr>
<td>Radiography</td>
<td>0.054 ± 0.014</td>
<td>0.072 ± 0.013</td>
<td>0.053 ± 0.004</td>
<td>0.140 ± 0.039</td>
<td>0.004 ± 0.001</td>
<td>0.158 ± 0.053</td>
</tr>
<tr>
<td>(average ± SD)</td>
<td>0.087 ± 0.022</td>
<td>0.090 ± 0.063</td>
<td>0.121 ± 0.029</td>
<td>0.173 ± 0.030</td>
<td>0.107 ± 0.036</td>
<td>0.326 ± 0.115</td>
</tr>
<tr>
<td>OCT (average ± minimum)$^3$</td>
<td>0.085/0.029</td>
<td>0.100/0.053</td>
<td>0.062/0.049</td>
<td>0.205/0.062</td>
<td>0.007/0.002</td>
<td>0.268/0.098</td>
</tr>
<tr>
<td>(maximum/minimum)$^3$</td>
<td>0.136/0.063</td>
<td>0.188/0.030</td>
<td>0.276/0.097</td>
<td>0.487/0.103</td>
<td>0.227/0.067</td>
<td>0.570/0.197</td>
</tr>
</tbody>
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*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.

$^3$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.](image)

![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.](image)
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