Nondestructive measurement of remaining dentin thickness using time-domain optical coherence tomography

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Abstract: *Purpose*: The ability of optical coherence tomography (OCT) to detect the remaining dentin thickness (RDT) in cases of erosive tooth wear was evaluated.

Methods: The labial surfaces of extracted bovine teeth were ground with wet silicon carbide papers ranging from #240-grit to #2,000-grit to create different RDTs. The time-domain (TD)-OCT imaging system was projected onto the specimen surface, and the areas of interest were scanned using a probe attached to a mounting device. A depth profile of backscattering along a line perpendicular to the object surface was generated (A-scan), and the RDT was obtained. After TD-OCT scanning, the specimens were sectioned longitudinally (mesial-distal), and the thicknesses were measured using laser scanning microscopy (LSM). The data obtained from the different measurements were subsequently compared. Bland-Altman comparison and the paired *t*-test were used at a significance level of 0.05.

Results: The agreement between the different measurement methods was analyzed to assess the intermethodology variation, with strong and positive correlations found for each group of measurements. The results indicated that the mean difference between the TD-OCT and LSM measurements was 7.857 ± 68.284 μm, with the 95% Bland-Altman limits of agreement ranging from −125.980 to 141.694 μm.

Conclusion: Although TD-OCT scanning has several limitations, it is a promising, nondestructive method for assessing RDT under the conditions of this study.

Keywords: dentin thickness measurement, optical coherence tomography, erosive tooth wear

Time-domain 型光干渉断層画像法を用いた残存象牙質厚径の非破壊測定

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要旨：目的：非破壊観察が可能な光干渉断層画像法（OCT）を用いて酸蝕歯の残存象牙質厚径（RDT）について評価した。

方法：ウシ下顎前歯の唇側面を耐水性 SiC ペーパーの #240 から #2,000 まで順次研磨することで，象牙質の残存厚径が異なる測定用試片を製作した。OCT については，Time-domain 型 OCT 装置からの照射光線が，これら測定用試片表面に垂直に照射されるよう調整し，装置付属のプローブを用いてスキャンした。測定は，A-scan mode で行い，測定範囲内の信号強度を得ることで試片の残存象牙質厚径の測定を行った。また，OCT 計測後の測定用試片を，近遠心方向に縦断し，縦断面の象牙質残存厚径を，レーザ走査型顕微鏡を用いて計測することで，OCT で得られた RDT と比較した。OCT およびレーザ走査型顕微鏡で得られた RDT について，Bland-Altman 分析および paired *t*-test を用いて，有意水準 5% の条件で統計学的検定を行った。

成績：異なる測定方法で得られた RDT の一致度を比較した結果，測定値間に強い正の相関が見られた。すなわち，OCT およびレーザ走査型顕微鏡で得られた RDT の平均の差は 7.857 ± 68.284 μm であり，Bland-Altman 分析の結果，95% 一致限界の −125.980 から 141.694 μm の範囲内であることが示された。

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結論：OCT を用いた測定はいくつかの制限があるものの，非破壊的に象牙質の残存歯質厚径の測定が可能であることが示された。

キーワード：象牙質厚径測定，光干渉断層画像法，酸蝕歯

Introduction

Erosive tooth wear has been defined as the loss of hard dental tissue caused by nonbacterial chemical attack [1]. In the early stages, erosive tooth wear is limited to the surface softening of the enamel and dentin. However, an extensive surface loss can occur as a result of demineralization and associated physical forces, such as brushing and attrition [2]. Results from longitudinal studies have shown that an increased number of teeth are affected by erosive tooth wear and that the severity of erosive tooth wear increases with increasing age [3]. Erosive agents can be classified as intrinsic (gastric acid) or extrinsic (foods and drinks), with increased attention paid to acidic diets, as there has been a dramatic growth in the consumption of acidic beverages in the past few decades. A link between erosive tooth wear and the intake of sweet, carbonated drinks was found, and other dietary elements have been reported to be associated with erosive tooth wear, including fruit juices, sports drinks, fresh fruits, vitamin C, vinegar, and herbal tea [4].

There are variabilities in the prevalence data for erosive tooth wear in the general population for both primary and permanent teeth. The results of a review paper [5] indicated that the mean number of teeth with facets of moderate to severe wear was 5.4, and 51% of the participants had four or more teeth with facets of moderate to severe wear. The acceptable amount of tooth wear is dependent on the expected life span of the teeth, which is different for primary teeth compared with permanent teeth. However, erosive damage to the permanent teeth that occurs in childhood may compromise the growing child's dentition over their entire lifetime and may require repeated and increasingly expensive restorations [6]. Therefore, early diagnosis of the tooth wear process in children and adults is important in enabling the initiation of appropriate preventive measures. In addition, early intervention can commence only if risk factors, as well as biological and behavior-modifying factors, are considered [7].

Diagnosis in the early stages of erosive tooth wear is often overlooked because there are a few signs and fewer, if any, symptoms. Therefore, determining the possible clinical course and progressive nature of erosive tooth wear is of importance for identifying the predisposing and exacerbating factors to enable better monitoring, prognoses, and prevention of further damage to teeth. Although the patient's clinical appearance is the most important feature used by dental professionals for the diagnosis of erosive tooth wear, it is difficult to visually assess the remaining dentin thickness (RDT). A number of methods have been developed to assess RDT, including cone-beam computed tomography [8], electrical resistance measurement [9], and ultrasonic measurement technique [10].

Optical coherence tomography (OCT) has been used for providing cross-sectional images of biologic structures based on the differences in tissue optical properties [11] and has also been employed for the determination of enamel remineralization [12]. Time-domain (TD) OCT can generate a depth scan (A-scan) by mechanically scanning the coherence gate along the depth range. The TD-OCT imaging system is able to generate *in vivo* optical cross-sections of the samples with a typical axial resolution of tens of micrometers and low-acquisition states of a few images per second (i.e., a few hundred A-scan/s). Therefore, TD-OCT might be beneficial for applications that require a wide scanning range or a high lateral resolution [13].

The purpose of this study was to evaluate the accuracy of RDT measurements using the TD-OCT imaging system compared with measurements by laser scanning microscopy (LSM) after grinding of the bovine tooth surface. We tested the hypothesis that there would be significant differences between TD-OCT and LSM measurements.

Materials and Methods

1. Specimen preparation

Five freshly extracted bovine incisors, without cracks or erosion, were cleaned and stored in physiological saline for up to 2 weeks. Teeth were mounted in cold-curing acrylic resin (Tray Resin II; Shofu, Kyoto, Japan) to expose the labial surface and then ground with wet #240-grit silicon carbide (SiC) paper

(Fuji Star Type DDC, Sankyo Rikagaku, Saitama, Japan) using water coolant to expose the dentin surface. Then, a sequence of SiC papers (ending with 2,000-grit) was used to create different RDTs. Specimens were cleaned with an ultrasonic bath (Quantrex 360; L&R Mfg., Kearmy, NJ, USA) in distilled water for 3 min.

2. OCT measurement

A focused light beam from the TD-OCT imaging system (J. Morita Mfg., Saitama, Japan) was projected onto locations of the specimen surface and scanned across the areas of interest using a probe attached to a mounting device.

Superluminescent diodes (DL-CS3184 B; DensLight Semiconductors, Singapore) with a central wavelength of 1310 ± 50 nm, spectral bandwidth of 40 nm, and optical output power of 7.5 mW were used as the light source. The emission light was coupled to a single-mode fiber-optic Michelson interferometer and delivered to the reference mirror and samples. The reference mirror was mounted on a linearly translating galvanometer, which was driven by a triangular voltage waveform with a fringe modulation frequency of 1 kHz. The light was reflected off the mirror back onto the retroreflector and reimaged on the reference arm fiber. The light beam scanned the sample surface point-by-point and line by line. A depth profile of backscattering along a line perpendicular to the object surface was generated (A-scan). These signals were amplified and demodulated by an amplifier; subsequently, the voltage from the lock-in amplifier was converted to a digital signal using a data acquisition board and then processed on a personal computer using Origin 9 analysis software (OriginLab, Northampton, MA, USA).

Three specific positions on the specimen were assigned to obtain the RDT measurement by TD-OCT for five different bovine teeth with three different measurement points (Fig. 1). Air was gently blown over the specimen surface for 10 s, and then the specimen was positioned under the probe of the TD-OCT, with the notch oriented toward the probe handle. The scanning probe connected to the TD-OCT device was fixed 2 mm from the sample surface. The thickness of the sample was determined by subtracting the vertical position of the reflected light of the pulp–dentin junction from the vertical position of the sample surface in the TD-OCT image, using an average refractive index (RI) of 1.540 [14].

3. LSM measurement

After performing the TD-OCT measurements, the specimens were sectioned longitudinally (mesial-distal) using a precision sectioning saw that was equipped with a diamond-impregnated blade (IsoMet 1000; Buehler, Lake Bluff, IL, USA). The sectioned surfaces were subsequently ground with wet SiC papers end-

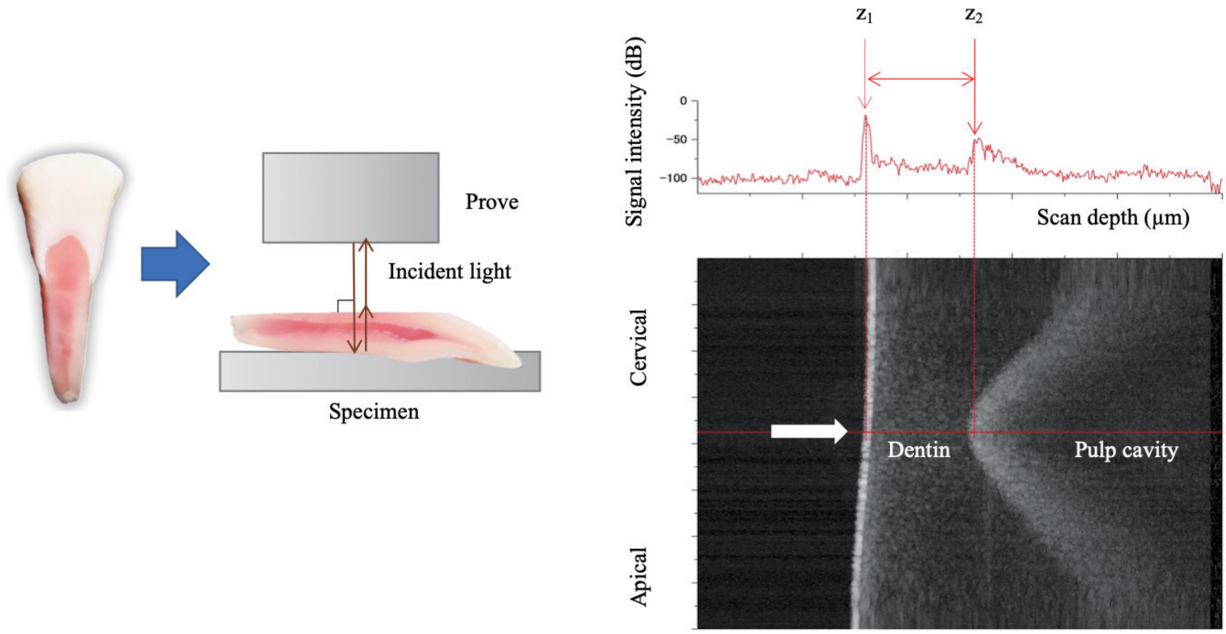

Fig. 1. TD-OCT two-dimensional tomography B-scan mode (lower) and the corresponding signal intensity profiles of the A-scan mode (upper) for the measurement of the remaining dentin thickness.

ing with 2,000-grit SiC paper. Specimens from approximately the same positions were observed using LSM (VK-8700 3 D; Keyence, Osaka, Japan). The excitation light had a maximum wavelength of 658 nm, and the excitation light intensity and photomultiplier amplification remained constant. The recorded image size was 81.5 × 71.5 μm^2, with a resolution of 1,024 × 768 pixels. Images were obtained for four different sites from each sample to determine the RDT.

4. Statistical analysis

The significance level of the normality test was set at α = 0.05. Data for each group were tested for homogeneity of variance (Bartlett's test) and normal distribution (Kolmogorov-Smirnov test). If the test's p-value was <0.05, the data were not normally distributed, and a nonparametric test, such as the Wilcoxon signed-rank test, was used instead of the paired t-test. However, if the p-value was >0.05, the data were deemed normally distributed, and the paired t-test was used. We used the Bland-Altman comparison method to evaluate the agreement in RDT values between the TD-OCT measurement and direct measurement using LSM. All statistical analyses were performed using a commercial statistical software package (SigmaPlot 11.2, Systat Software, Chicago, IL, USA).

Results

The RDT values obtained using TD-OCT and LSM are shown in Table 1. The correlations in specimen thicknesses between the TD-OCT and LSM measurements are presented in Fig. 2. The agreement between the different measurement methods was analyzed to assess the variation between methodologies, and we found strong correlations for each group of measurements (R = 0.996). The Bland-Altman comparison method was used to determine the agreement in RDT between the TD-OCT and the LSM measurements (Fig. 3). The results indicated that the mean difference between the TD-OCT and the LSM measurements were 7.857 ± 68.284 μm, with a 95% Bland-Altman limit of agreement ranging from −125.980 to 141.694 μm.

Discussion

Determining the progression of pathological tooth wear over time is essential for the initiation of the most appropriate treatment and to ensure a good prognosis for the teeth [15]. Surveillance involves a series of tests and measurements that are repeated

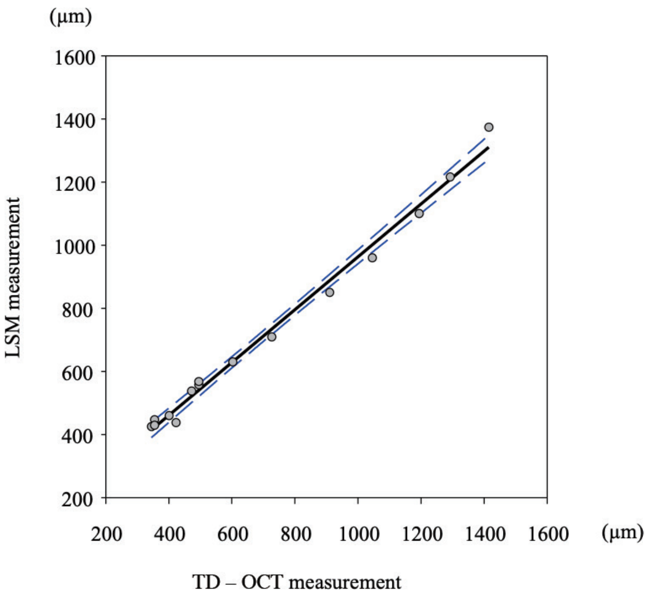

Fig. 2. Comparison of methods using a linear regression analysis of the data presented in Table 1. The solid line denotes the linear regression line, and the dashed line denotes the line of identity.

Table 1 Comparison of RDT values measured by TD-OCT and LSM methods

Specimen	#1			#2			#3			#4			#5		
Measurement point	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
OCT value	345 (18)	355 (21)	373 (19)	401 (25)	423 (20)	429 (20)	472 (20)	495 (17)	603 (17)	726 (23)	910 (19)	1045 (27)	1194 (30)	1292 (35)	1415 (40)
LSM value	425 (16)	429 (16)	447 (20)	430 (18)	438 (15)	458 (18)	538 (18)	568 (19)	630 (22)	709 (25)	850 (21)	960 (19)	1100 (28)	1216 (30)	1374 (32)

Unit: μm, n = 5, mean values and (standard deviations) for each specimen averaged of three times measurements.

Values connected by vertical lines indicate not significantly different ($p > 0.05$).

after a specified time period to assess whether a particular phenomenon is progressive. This is the only method to determine whether tooth wear is progressive or stationary, and monitoring is essential for treating tooth wear. If the wear process is aggressive, immediate treatment is needed, with a focus on its main cause [16]. In the present study, we evaluated the reliability of TD-OCT measurements to determine the RDT and then correlated the results with LSM measurements. Because all TD-OCT measurements confirmed the surface of the specimen and the dentin–pulp junction, we determined that all of the measurements using ground dentin specimens in the present study were acceptable. Because of the different RDTs in the ground-tooth specimens, TD-OCT could also be used to determine a wide range of dentin thicknesses from 345 μm to 1,415 μm.

We examined the differences between the measured values obtained as pairs from the TD-OCT and LSM measurement methods using the Bland-Altman method [17]. The mean difference between the paired measurement values is known as "bias (systemic error)," and the standard deviation of the difference between the measurement values is known as "precision." One frequently used method to represent the results of this analysis is the Bland-Altman plot, also known as the difference against the mean plot (Fig. 3). This graph is obtained by plotting the differences between the methods on the y-axis and the average value of the measured pairs on the x-axis. The reason for plotting the average value obtained from the two methods on the x-axis is that the true value is closer to the average value, and the relationship between the differences between the measured values and the magnitude of the measured value can be evaluated more precisely [18]. The results of the present study showed good agreement between the TD-OCT and LSM measurements for determining RDT and also demonstrated that TD-OCT was accurate and effective for measuring dentin thickness.

The imaging depth used for OCT depends not only on the device's attributes and specifications but also on the optical properties of the tooth substrate. In this context, the RI is an important parameter of light propagation in tooth specimens, and scattering is the final result of the local variation in RI [19]. The signal attenuation through dentin is greater than that of enamel because dentin contains approximately 55 vol% mineral, 30 vol% organic material, and 15 vol% water [20], all of which scatter and absorb the near-infrared light. In addition, the presence and orientation of dentinal tubules have a great impact on light scattering and attenuation [21]. Although the RDT measured by LSM is assumed to represent the actual dimension of the dentin, the depth measured by TD-OCT is affected by the optical path length in the dentin, and thus, it is not possible to directly show the physical dimension unless the RI values are given

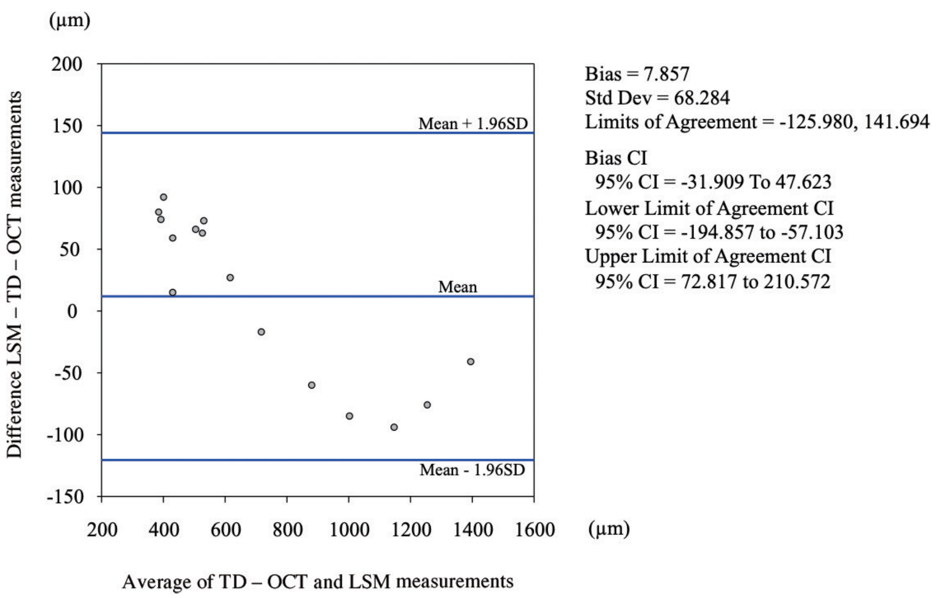

Fig. 3. Bland-Altman plot of the different measurement methods for RDT (bias: mean of difference, SD: standard deviation, CI: confidence interval).

in advance [22]. Previous studies that calculated the RIs of dentin using OCT [23] used an RI value of 1.540 to convert the optical thickness measurements of RDT to actual values over a wide range of readings. In the present study, the value obtained by subtracting the measurement thickness of TD-OCT from the measurement thickness of LSM tended to be negative value with increasing RDT.

The results of this study show that the quantitative measurement of RDT using TD-OCT is a simple method that may provide information on changes in dentin depth [24]. On the other hand, care was taken not to desiccate the tooth during measurement because it is more difficult to visualize the dentin-pulp junction in scans if the specimen dries out. Tooth dehydration leads to increased light scattering because of the RI mismatch, thereby impeding propagation into the deeper area of the specimen [25]. A previous study demonstrated the influence of internal hydration on the transparency of enamel and recommended that the teeth be kept well hydrated for proper OCT measurement [26]. Although there is no consensus on the optimal hydration status of teeth during OCT measurements, some attention should be paid to the water status of the specimens during measurements.

Taking into consideration the limitations of the conditions applied in this *in vitro* study, the TD-OCT measurement might be a reliable, nondestructive method for the evaluation of RDT. TD-OCT is a promising imaging technique that can monitor minute changes in dentin thickness, and it can be used as an effective tool for observing the progression of tooth wear over time.

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Conflicts of interest

The authors of this manuscript certify that they have no proprietary, financial, or other personal interest of any nature or kind in terms of any product, service, and/or company that is presented in this article.

References

1) Schlueter N, Luka B (2018) Erosive tooth wear - a review on global prevalence and on its prevalence in risk groups. Br Dent J 224, 364-370.
2) Alvarez-Arenal A, Alvarez-Menendez L, Gonzalez-Gonzalez I, Alvarez-Riesgo JA, Brizuela-Velasco A, deLlanos-Lanchares H (2019) Non-carious cervical lesions and risk factors: A case-control study. J Oral Rehabil 46, 65-75.
3) Jaeggi T, Lussi A (2014) Prevalence, incidence and distribution of erosion. Monogr Oral Sci 25, 55-73.
4) O'Toole S, Mullan F (2018) The role of the diet in tooth wear. Br Dent J 224, 379-383.
5) Cunha-Cruz J, Pashova H, Packard JD, Zhou L, Hilton TJ (2010) Tooth wear: prevalence and associated factors in general practice patients. Community Dent Oral Epidemiol 38, 228-234.
6) Lussi A, Carvalho TS (2014) Erosive tooth wear: a multifactorial condition of growing concern and increasing knowledge. Monogr Oral Sci 25, 1-15.
7) Wetselaar P, Lobbezoo F (2016) The tooth wear evaluation system: a modular clinical guideline for the diagnosis and management planning of worn dentitions. J Oral Rehabil 43, 69-80.
8) Xu J, He J, Yang Q, Huang D, Zhou X, Peters OA, Gao Y (2017) Accuracy of cone-beam computed tomography in measuring dentin thickness and its potential of predicting the remaining dentin thickness after removing fractured instruments. J Endod 43, 1522-1527.
9) Tielemans S, Bergmans L, Duyck J, Naert I (2007) Evaluation of a preparation depth controlling device: a pilot study. Quintessence Int 38, 135-142.
10) Ghorayeb SR, Bertoncini CA, Hinders MK (2008) Ultrasonography in dentistry. IEEE Trans Ultrason Ferroelectr Freq Control 55, 1256-1266.
11) Katkar RA, Tadinada SA, Amaechi BT, Fried D (2018) Optical coherence tomography. Dent Clin North Am 62, 421-434.
12) Murayama R, Nagura Y, Yamauchi K, Moritake N, Iino M, Ishii R, Kurokawa H, Miyazaki M, Hosoya Y (2018) Effect of a coating material containing surface reaction-type pre-reacted glass-ionomer filler on prevention of primary enamel demineralization detected by optical coherence tomography. J Oral Sci 60, 367-373.
13) Strom AR, Cortés DE, Rasmussen CA, Thomasy SM, McIntyre K, Lee S-F, Kass PH, Mannis MJ, Murphy CJ (2016) *In vivo* evaluation of the cornea and conjunctiva of the normal laboratory beagle using time- and Fourier-domain optical coherence tomography and ultrasound pachymetry. Vet Ophthalmol 19, 50-56.
14) Meng Z, Yao XS, Yao H, Liang Y, Liu T, Li Y, Wang G, Lan S (2009) Measurement of the refractive index of human teeth by optical coherence tomography. J Biomed Opt 14, 034010.

15) Muts EJ, van Pelt H, Edelhoff D, Krejci I, Cune M (2014) Tooth wear: a systematic review of treatment options. J Prosthet Dent 112, 752-759.
16) Mehta SB, Banerji S, Millar BJ, Suarez-Feito JM (2012) Current concepts on the management of tooth wear: part 1. Assessment, treatment planning and strategies for the prevention and the passive management of tooth wear. Br Dent J 212, 17-27.
17) Bland JM, Altman DG (1986) Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1(8476), 307-310.
18) Kim HY (2013) Statistical notes for clinical researchers: Evaluation of measurement error 2: Dahlberg's error, Bland-Altman method, and Kappa coefficient. Restor Dent Endod 38, 182-185.
19) Knüttel A1, Bonev S, Knaak W (2004) New method for evaluation of *in vivo* scattering and refractive index properties obtained with optical coherence tomography. J Biomed Opt 9, 265-273.
20) Marshall GW Jr, Marshall SJ, Kinney JH, Balooch M (1997) The dentin substrate: structure and properties related to bonding. J Dent 25, 441-458.
21) Hariri I, Sadr A, Shimada Y, Tagami J, Sumi Y (2012) Effects of structural orientation of enamel and dentine on light attenuation and local refractive index: an optical coherence tomography study. J Dent 40, 387-396.
22) Tan X, Agrawal A, Hammer DX, Ilev I (2019) Application of optical coherence tomography and optical path length method for monitoring corneal thickness and refractive index change during corneal cross-linking. Appl Opt 58, 4616-4621.
23) Hariri I, Sadr A, Nakashima S, Shimada Y, Tagami J, Sumi Y (2013) Estimation of the enamel and dentin mineral content from the refractive index. Caries Res 47, 18-26.
24) Uhlhorn SR, Borja D, Manns F, Parel JM (2008) Refractive index measurement of the isolated crystalline lens using optical coherence tomography. Vision Res 48, 2732-2738.
25) Chan KH, Chan AC, Darling CL, Fried D (2013) Methods for monitoring erosion using optical coherence tomography. Proc SPIE Int Soc Opt Eng 8566, 856606.
26) Chung S, Fried D, Staninec M, Darling CL (2011) Multispectral near-IR reflectance and transillumination imaging of teeth. Biomed Opt Express 2, 2804-2814.