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Full Length Article

Assessment of enamel cracks at adhesive cavosurface margin using three-dimensional swept-source optical coherence tomography

Tomoko Tabata[a], Yasushi Shimada[a,b,*], Alireza Sadr[c], Junji Tagami[a], Yasunori Sumi[d]

[a] Cariology and Operative Dentistry, Oral Restitution Department, Graduate School of Medical and Dental Sciences, Tokyo Medical and Dental University, 1-5-45 Yushima, Bunkyo-ku, Tokyo, 113-8549, Japan
[b] Department of Operative Dentistry, Graduate School of Medicine and Dentistry, Okayama University, 2-5-1 Shikata-cho, Kita-ku, Okayama, 700-8525, Japan
[c] Biomimetics Biomaterials Biophotonics & Technology Laboratory, Department of Restorative Dentistry, University of Washington School of Dentistry, 1959 NE Pacific St. Box 357456, Seatle, WA, 98195-7456, USA
[d] National Center for Geriatrics and Gerontology, Department for Advanced Dental Research, Center of Advanced Medicine for Dental and Oral Diseases, 36-3, Gengo, Morioka, Obu, Aichi, 474-8511, Japan

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ABSTRACT

Objectives: Swept-source optical coherence tomography (SS-OCT) can construct cross-sectional images of internal biological structures. The aim of this study was to evaluate enamel cracks at the cavosurface margin of composite restorations using SS-OCT.
Methods: Bowl-shaped cavities were prepared at two locations (mid-coronal and cervical regions) on the enamel surface of 60 bovine teeth. Half of the cavities (30) were treated with phosphoric acid gel. A two-step self-etch adhesive (Clearfil SE Bond) was applied to all cavities and a flowable composite was placed in bulk. After 7 days in water at 37 °C, three-dimensional (3D) images of the specimens were obtained using SS-OCT, and cross-sectional views of the cavosurface margin were examined. Presence and extent of enamel cracks along the cavosurface margin circumference were evaluated using a 5-point scale. The results were statistically compared with Wilcoxon rank sum test with Bonferroni correction.
Results: 3D SS-OCT could detect enamel cracks at the cavosurface margin of composite restorations. Cervical regions caused more enamel cracking than mid-coronal regions. Phosphoric acid etching increased the incidence of enamel cracks compared with the preparations without etching.
Conclusion: SS-OCT can be used to detect enamel cracks at the margins of composite restorations noninvasively. Presence and extent of enamel cracks depended on the enamel region and bonding protocol.
Clinical significance: SS-OCT can be used to detect enamel cracks at the margins of composite restorations noninvasively. Selective phosphoric acid etching of the enamel significantly increased the incidence of marginal cracks, especially in cervical preparation.

1. Introduction

Advancements in adhesive technology have enabled less invasive dental treatment in an invisible repair manner and the indications of direct composite resins have expanded to cases with extensive tooth structure loss, including the proximal contact or cervical areas. However, the resin-based restorative materials shrink during the polymerization process, thereby creating a gap at the resin-tooth interface or a crack in the enamel at the cavosurface margin [1–3].

Enamel cracks at the margins of composite restorations were first reported by Fusayama [1] who suggested that this phenomenon was due to polymerization contraction stress. Clinically, the margin with enamel crack appears whitish after adjustment of the cavosurface margin of composite restoration. A micro-crack in the cavosurface enamel can result in post-operative sensitivity and formation of secondary caries [4,5].

The magnitude of polymerization contraction stress depends on many factors, including the geometry of the prepared cavity, compositional and curing characteristics of the composite material, and photo-curing strategy. Current evidence suggests that enamel cracks occur at 43%–92% of the circumference of the restoration [2,6]. Christensen et al. [2] stated that the resin formulation was significantly associated with shrinkage and formation of white lines rather than the design and intensity of the curing light.

Enamel mainly consists of highly mineralized prisms with micro-structural anisotropy, while cervical enamel contains randomly or-

* Corresponding author at: Department of Operative Dentistry, Graduate School of Medicine and Dentistry, Okayama University, 2-5-1 Shikata-cho, Kita-ku, Okayama, 700-8525, Japan
E-mail address: shimada.ope@okayama-u.ac.jp (Y. Shimada).

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iented hydroxyapatite crystals and atypical enamel prisms [7]. Although this morphological difference in enamel location could potentially affect the occurrence of cracking, limited information is available in this regard in the literature.

Optical coherence tomography (OCT) is an emerging cross-sectional imaging method for observation of internal biological structures. OCT helps in visualizing differences in the optical properties of tissues, which includes the effects of both optical absorption and scattering [8]. The swept-source (SS) type of OCT (SS-OCT) is a highly sensitive and improved variation of the fast Fourier transformation algorithm [9]. In this article, SS-OCT was investigated as a diagnostic tool for enamel cracks at the margins of resin composite restorations. Influence of cavity locations prepared with the tooth structure and effect of selective phosphoric acid etching were evaluated using SS-OCT.

2. Materials and methods

2.1. SS-OCT observation

The SS-OCT system (Yoshida Dental MFG, Tokyo, Japan) used in this experiment is a frequency domain OCT technique that measures the magnitude and time delay of reflected light in order to construct a depth profile. The light source in this system sweeps the nearinfrared spectrum from 1240 nm to 1380 nm, centered at 1310 nm at a 50 kHz rate. Three dimensional (3D) data set is obtained at optical resolution in air of 11 μm in depth and 40 μm in width and length [10] (Table 1).

2.2. Cavity preparation and assessment of enamel crack using SS-OCT

The materials used in this study and their compositions are listed in Table 2. Freshly extracted bovine incisors were used in this study. A cavity was prepared on one of the two enamel locations on each specimen; mid-coronal or cervical regions. The round bowl-shaped cavities were 3 mm in diameter and 2 mm in depth, prepared using a carborundum point (#SF22, Shofu, Kyoto, Japan) and super-fine diamond bur (#SF440, Shofu) attached to a rotary grinding instrument under copious water. After the preparation, all the cavities were subjected to SS-OCT observation to check the marginal integrity. Cavities without cavosurface enamel crack forming due to the bur cutting were chosen and employed; as a result 60 cavities (30 in each enamel location) were used in this study.

The cavosurface enamel margin of cavities in 15 randomly selected specimens in each enamel location was chosen and treated with 40% phosphoric acid (K-etchant Gel; Kuraray Noritake Dental, Inc.,Tokyo, Japan) for 10 s, while the other 15 specimens were left untreated. All the 60 cavities were then treated with a self-etching primer and bonding system (Clearfil SE Bond, Kuraray Noritake Dental, Tokyo, Japan) according to the manufacturer's instructions, followed by bulk filling with flowable resin composite (Estelite Flow Quick, Shade A2, Tokuyama Dental,Tainai,Japan), photocured for 20 s using a halogen light curing unit (Optilux 501, Kerr Corporation, Orange, CA, USA) with a power density of 550–600 mW/cm^2.

The restored surface was then polished using a microengine hand piece with water spray and a silicone point to remove the extruded adhesive and resin from the cavity. In this manner, specimens were prepared in four groups (n = 15) with respect to enamel location (mid-coronal or cervical) and phosphoric acid etching (with or without).

Table 1
Swept-source optical coherence tomography (SS-OCT) system specification used in this study.

Scan axis	Effective imaging depth (in air)	Point	Resolution (in air)
Depth (A)	8 mm	1024	11 μm
Lateral (B)	10 mm	400	40 μm
Axial (C)	10 mm	400	40 μm

This SS-OCT system incorporated a hand-held probe with a power of less than 15.0 mW. The spectral bandwidth of the laser was 140 nm centered at 1310 nm at a 50-kHz sweep rate.

After storage in water at 37 °C for 7 days, a 3D data set of the specimen was obtained using the SS-OCT system (Fig. 1). The 3D data set included horizontal cross-sectional views of the cavosurface margins up to depth of 1 mm. The extent of enamel cracks along the cavosurface margin circumference was evaluated and scoring was performed using the following 5-point rank scale (Fig. 2):

0 = no enamel crack,

1 = an enamel crack of less than 1/4 of the cavosurface margin circumference,

2 = an enamel crack of ≥ 1/4 and < 1/2 of the cavosurface margin circumference,

3 = an enamel crack of ≥ 1/2 and < 3/4 of the cavosurface margin circumference, and

4 = an enamel crack of ≥ 3/4 of the cavosurface margin circumference,

The number of cavities for each score was recorded and statistically analysed with a critical value $\alpha = 0.05$.

2.3. Cross-sectioning and laser scanning confocal microscope observation

Five representative cavities with enamel cracks as observed by SS-OCT were selected from each experimental group for confirmatory observations using a laser scanning confocal microscope (3D Laser Scanning Confocal Microscope; Keyence, Osaka, Japan). The specimens were ground and polished using a high-speed rotating device (Automatic Lapping Machine ML-160A, MARUTO INSTRUMENT CO., LTD.) equipped with a diamond point and silicon carbide paper under copious water flow to expose the sagittal section of the cavity. The surface was further polished with diamond paste down to 3 μm under running water. Then, the specimens were viewed under the laser scanning confocal microscope at an optical magnification of × 10.

2.4. Statistical analysis

The results were statistically analysed by using statistical software package (SPSS). Cross-sectional images near the cavity margin were extracted from 3D stereoscopic images constructed from restorations using SS-OCT. Since the distribution of data was not normal, non-parametric tests were performed. Wilcoxon rank sum test with Bonferroni correction was used to determine whether there was any difference between the location and application of enamel etching ($\alpha = 0.05$).

3. Results

3D SS-OCT could detect enamel cracks at cavosurface margin of composite restorations. Enamel cracks on the images were clearly distinguished as bright lines caused by increased OCT signal intensity.

Data regarding the presence and extent of enamel cracks at the mid-coronal and cervical cavosurface margins are shown in Fig. 3. There were significantly more cracks in the cervical regions than in the mid-coronal regions ($p < 0.05$). In comparison with preparations without etching, those with phosphoric acid etching significantly increased the number of enamel cracks ($p < 0.05$).

The confocal microscopy images confirmed the crack location on OCT cross-section (Fig. 4). These cracks predominantly initiated adjacent to the cavosurface margin and extended along the interface towards the DEJ, and occasionally reached the bonded interface.

4. Discussion

Enamel microcracks at the cavity margin of composite restorations and marginal leakage sometimes cause marginal discoloration leading

Table 2
Materials used in this study.

Materials	Composition
K-etchant Gel (Kuraray Noritake Dental Tokyo, Japan)	Phosphoric acid, Colloidal silica, Water, Dyes
Clearfil SE Bond (Kuraray Noritake Dental Tokyo, Japan)	Primer: MDP, HEMA,Hydrophilic dimethacrylate,Photoinitiator, Water Adhesive: MDP, Bis-GMA, HEMA, Hydrophobic dimethacrylate, Camphorquinone,Silanated colloidal silica
Estelite Flow Quick (Tokuyama Dental,Tainai, Japan)	Bis-MPEPP, TEGDMA, UDMA, Silica-zirconia filler, Silica-titania fillers, CQ

Abbreviations; Bis-GMA, Bisphenol A diglycidylmethacrylate; Bis-MPEPP, Bisphenol A polyethoxy methacrylate; CQ, Camphorquinone; HEMA, 2-Hydroxyethyl methacrylate; MDP, 10-Methacryloyloxydecyl dihydrogen phosphate; TEGDMA, Triethylene glycol dimethacrylate; UDMA, Urethane dimethacrylate.

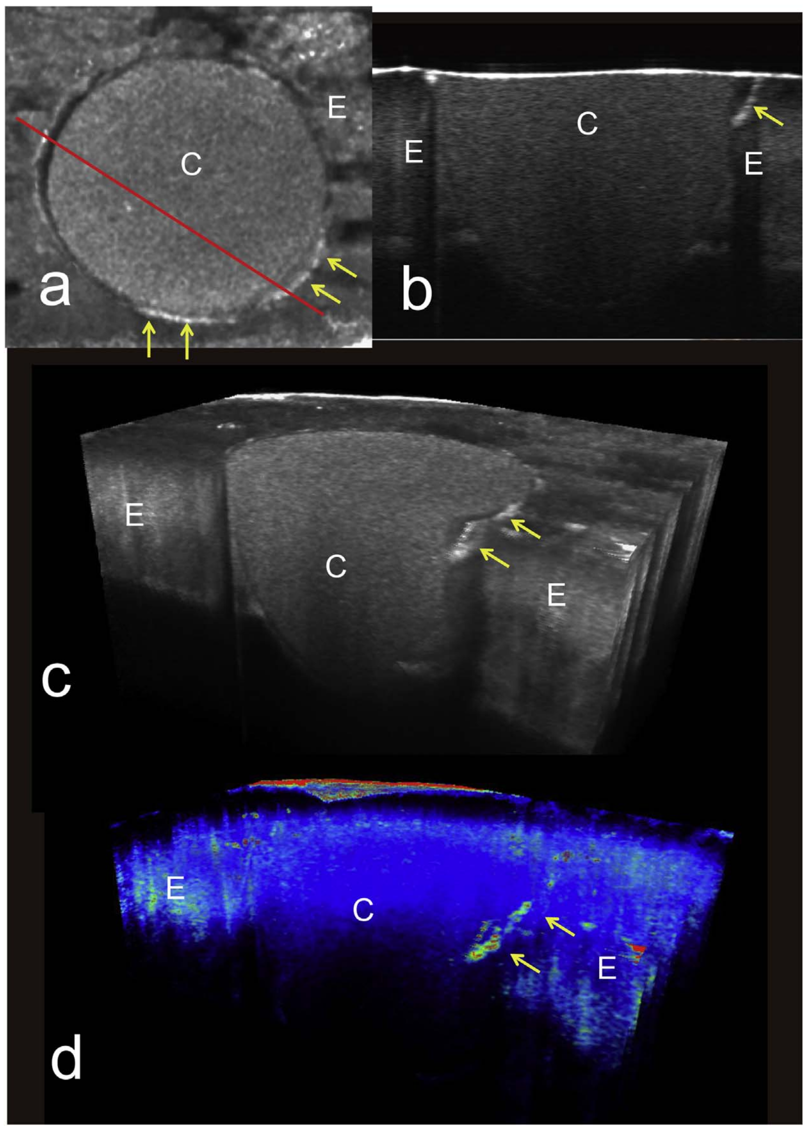

Fig. 1. (a) Horizontal veiw of cavosurface margin in gray-scale two-dimentional (2D) SS-OCT image. Enamel cracks (arrow) are identified as bright line near the margin. (b) Cross-sectional SS-OCT image of composite restoration along red line in (a). Gray-scale image. Enamel crack present near the margin penetrates into the subsurface resin-enamel interface at the subsurface zone (arrow). (c) A gray-scale three-dimensional (3D) SS-OCT image of (a) and (b). (d) Image processing and permeabilization of (c) to pick up the cavosurface enamel crack displayed as bright line (arrow). C: composite resin, E: enamel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

to secondary caries and pulp irritation [4,5]. While marginal leakage depend on bonding to enamel, prevention of cavosurface enamel cracks in adhesive dentistry is clinically challenging because cracks may occur even with the use of a current adhesive system capable of excellent bonding. In this study, 3D SS-OCT was used to detect enamel cracks at the cavosurface margin to evaluate the influence of cavity location and selective enamel etching with phosphoric acid. The results of this study clearly showed that SS-OCT could detect enamel cracks at the margin, depicted as bright lines within enamel that were distinguishable from intact enamel and interfacial gap, because the signal reflection from an enamel crack enhances the brightness of the SS-OCT image.

It is well known that the degree of reflection is dependent on the contrast of the refractive indices (n) of the media [11–13]. In a previous study on enamel and dentin measurements by OCT using an optical path-length-matching method, the n values were calculated as 1.63 and 1.55, respectively [12,13]. For detection of enamel cracks, the crack

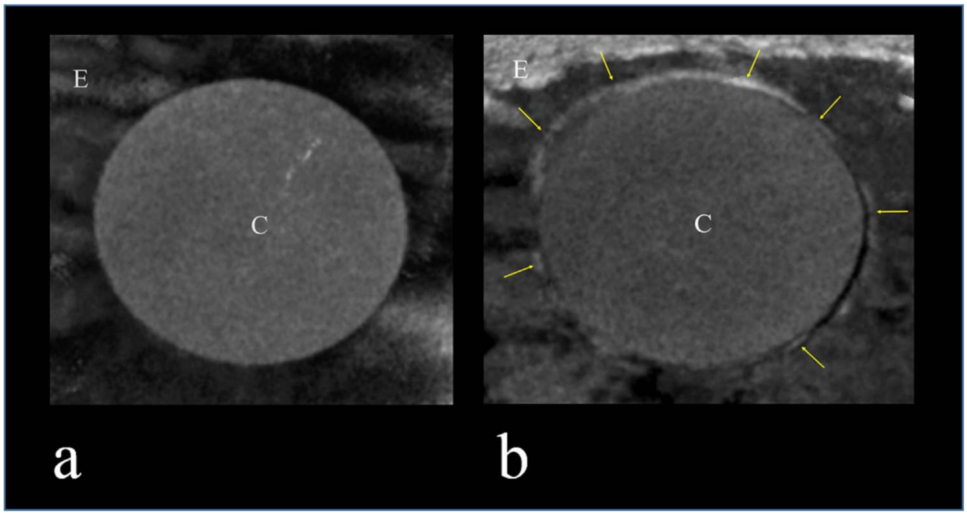

Fig. 2. Horizontal view of gray-scale two-dimensional (2D) SS-OCT image. (a) A SS-OCT image of a sample with no enamel crack (score 0). (b) A SS-OCT image of a sample with an enamel crack of > 3/4 of the cavosurface margin circumference (score 4). C: composite resin, E: enamel, Arrow: enamel crack.

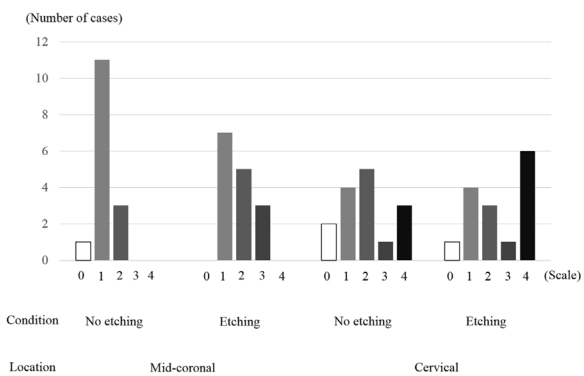

Fig. 3. Extent of enamel cracks at the mid-coronal and cervical cavosurface margins. There were more cracks at Cervical than Mid-coronal ($p < 0.05$). Etching increased the incidence of enamel cracks at both Mid-coronal and Cervical than No etching ($p < 0.05$). There was a significant difference between Mid-coronal and Cervical and between No etching and Etching.

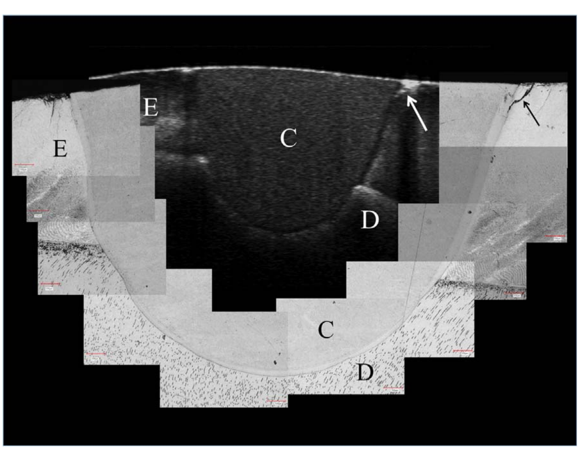

Fig. 4. A two-dimensional (2D) SS-OCT image and corresponding laser scanning confocal microscopic image. The presence of an enamel crack was displayed as a bright line in SS-OCT (white arrow), which corresponded to the enamel crack (black arrow) on the laser scanning confocal microscopic image. C: composite resin, E: enamel, D:dentin.

space was assumed to be filled with air or water (n approximately 1.33). Nonetheless, the discrepancy in the value of n was significant for signal peaks at the fracture border [9].

A possible factor contributing to the formation of white lines is the occurrence of undesirable scratches or surface features produced by the diamond burs during preparation [14]. In this study, SS-OCT scanning of the enamel margin was performed soon after preparation to avoid the inclusion of a fractured enamel. There is much evidence that polymerization shrinkage occurs after gelation and that curing results in the build-up of stress, which compromises the integrity of the marginal seal [6,15]. When the bonding to enamel and the copolymerization of adhesive and composite are strong and resist separation, the stress is generated within enamel and along the bonded interface. Therefore, the polymerization contraction of the superficial layer of the light-cured composite resin can separate the marginal enamel rods from the neighboring rods if the chemical bond of the composite to the enamel wall is superior to the fracture toughness of the enamel rods [16]. It has been demonstrated that light-cured resin composites generate higher polymerization shrinkage stresses (or higher stress generation rates) than chemically cured composites because the former does not exist in a gel stage for a very long time [17,18]. Consequently, separation of enamel prisms rarely occurs with self-cured composite resins and can be prevented by preparing the enamel wall with a transverse section of enamel prisms [1].

Although visco-elastic relaxation mechanisms were not considered in this study, the use of a flowable composite was believed to have a greater capacity to allow for the release of generated stress for polymerization over the conventional composite placed in bulk [6].

In this study, the frequency of enamel cracks at the cavosurface margin was dependent on the cavity location and difference in the prismatic orientation at the cavity wall. Furthermore, phosphoric acid etching significantly deteriorated integrity of enamel adjacent to the adhesive restoration bonded with a self-etching adhesive system.

Although there were fewer cavosurface cracks with the use of self-etching adhesive, enamel cracks still formed in coronal and cervical cavities. On the other hand, marginal discoloration with the use of self-etching adhesive systems is common when the composite is extended over the sound enamel because of the weak bonds of the mild self-etch adhesives to the uncut enamel [19]. Kubo et al. [20] reported that self-etching adhesives could not prevent leakage at the enamel margin even when the manufactures' instructions are strictly followed. From the viewpoint of sealing the enamel margin, the clinical performance of the phosphoric acid etching system on the uncut enamel was superior to that of the self-etching adhesive system. Consequently, selective-etching of the enamel around a prepared cavity margins should be mainly directed at the uncut enamel over which the composite will extend. This optional process can provide good bonding to enamel while protecting the cavosurface enamel from paramarginal fractures. Further studies are necessary to formulate an appropriate protocol to prevent the formation of white lines at the margins of composite restorations.

In this study, the cervical region was more prone to enamel cracks than the mid-coronal regions. The mineral content of the cervical enamel is reported to be lower than that of the mid-coronal regions, as determined by microradiographic measurements [21,22], and is correlated with higher contents of $CO_3{}^{2-}$ and magnesium. The structurally integrated carbonate ions in the apatite lattice affect the chemical stability of the cervical enamel resulting in a higher susceptibility to phosphoric acid etching [23]. The higher frequency of enamel cracks in the cervical region is probably due to weakening of the enamel after phosphoric acid etching.

Within the limitation of this study, enamel cracks at the cavosurface margin of the composite restorations were clearly observed as white lines by SS-OCT in the mid-coronal and cervical regions. Moreover, selective phosphoric acid etching of the enamel significantly increased the occurrence of marginal cracks, especially in a cervical preparation. Therefore, a revised protocol for composite restoration appears necessary to protect the enamel from paramarginal fractures. Although the bonding performance of self-etching adhesive systems is reported as excellent in the literature, further studies are necessary to avoid the formation of white margins in adhesive esthetic dentistry.

5. Conclusion

In this study, 3D SS-OCT was useful to nonivasively detect enamel cracks at the margins of composite restorations. The presence and extent of enamel cracks were dependent on the region of preparation and bonding protocol.

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References

[1] T. Fusayama, Indication for self-cured and light-cured adhesive composite resins, J. Prosthet. Dent. 67 (1992) 46–51.
[2] R.P. Christensen, T.M. Palmer, B.J. Ploeger, M.P. Yost, Resin polymerization problems are they caused by resin curing lights, resin formulations, or both? Compend. Contin. Educ. Dent. 20 (Suppl) (1999) S42–S54.
[3] J. Kanca III, B.I. Suh, Pulse activation: reducing resin-based composite contraction stresses at the enamel cavosurface margins, Am. J. Dent. 12 (1999) 107–112.
[4] M. Sunada, L. Han, A. Okamoto, Crack initiation of tooth with aging and clinical care, Niigata. Dent. J. 32 (2002) 275–283.
[5] L. Han, M. Sunada, M. Fukushima, Enamel cracks and care techniques, Quintessence 23 (2004) 148–154.
[6] B. Kahler, M.V. Swain, A. Kotousov, Comparison of an analytical expression of resin composite curing stresses with in vitro observations of marginal cracking, Am. J. Dent. 23 (2010) 357–364.
[7] Y. Shimada, D. Kikushima, J. Tagami, Micro-shear bond strength of resin-bonding systems to cervical enamel, Am. J. Dent. 15 (2002) 373–377.
[8] Y. Shimada, A. Sadr, Y. Sumi, J. Tagami, Application of optical coherence tomography (OCT) for diagnosis of caries, cracks and defects of restorations, Curr. Oral. Health Rep. 2 (2015) 73–80.
[9] K. Imai, Y. Shimada, A. Sadr, J. Tagami, Y. Sumi, Noninvasive cross-sectional visualization of enamel cracks by optical coherence tomography, J. Endod. 38 (9) (2012) 1269–1274.
[10] T. Ueno, Y. Shimada, K. Matin, Y. Zhou, I. Wada, A. Sadr, Y. Sumi, J. Tagami, Optical analysis of enamel and dentine caries in relation to mineral density using swept-source optical coherence tomography, J. Med. Imaging 3 (July (3)) (2016) 035507.
[11] M.G. Sowa, D.P. Popescu, J.R. Friesen, M.D. Hewko, L.P. Choo-Smith, A comparison of methods using optical coherence tomography to detect demineralized regions in teeth, J. Biophotonics 4 (11–12) (2011) 814–823.
[12] I. Hariri, A. Sadr, Y. Shimada, J. Tagami, Y. Sumi, Effects of structural orientation of enamel and dentine on light attenuation and local refractive index: an optical coherence tomography study, J. Dent. 40 (2012) 387–396.
[13] Z. Meng, X.S. Yao, H. Yao, Y. Liang, T. Liu, Y. Li, G. Wang, S. Lan, Measurement of the refractive index of human teeth by optical coherence tomography, J. Biomed. Opt. 14 (3) (2009) 034010.
[14] K. Nishimura, M. Ikeda, T. Yoshikawa, M. Otsuki, J. Tagami, Effect of various grit burs on marginal integrity of resin composite restorations, J. Med. Dent. Sci. 52 (2005) 9–15.
[15] K.D. Jörgensen, E. Asmussen, H. Shimokobe, Enamel damages caused by contracting restorative resins, Scand. J. Dent. Res. 83 (1975) 120–122.
[16] L. Han, A. Okamoto, M. Fukushima, M. Iwaku, Microcracks in the marginal enamel due to composite restoration, Jpn. J. Conserv. Dent. 32 (1989) Autumn session No. A51.
[17] R.M. Carvalho, J.C. Pereira, M. Yoshiyama, D.H. Pashley, A review of polymerization contraction: the influence of stress development versus stress relief, Oper. Dent. 21 (1996) 17–24.
[18] A.J. Feilzer, A.J. de Gee, C.L. Davidson, Setting stresses in composite for two different curing modes, Dent. Mater. 9 (1993) 2–5.
[19] M. Ferrari, Handling of resin composite in anterior teeth, in: G. Dondidall'Orologio, C. Parati (Eds.), Factors Influencing the Quality of Composite Restorations, Theory and Practice, Ariesdue S.r.l. Publishers, Carimate Italy, 1997, pp. 121–137.
[20] S. Kubo, H. Yokota, Y. Sata, Y. Hayashi, Microleakage of self-etching primers after thermal and flexural load cycling, Am. J. Dent. 32 (2001) 142–146.
[21] C. Robinson, J.A. Weatherell, A.S. Hallsworth, Variation in composition of dental enamel within thin ground tooth sections, Caries Res. 5 (1971) 44–57.
[22] H.M. Theuns, J.W. van Dijk, W.L. Jonngebloed, A. Groeneveld, The mineral content of human enamel studied by polarizing microscopy, microradiography and scanning electron microscopy, Arch. Oral. Biol. 28 (1983) 797–803.
[23] F. Taube, M. Marczewski, J.G. Norén, Deviations of inorganic and organic carbon content in hypomineralised enamel, J. Dent. 43 (2015) 269–278.