Visualization of interfacial adhesive defects at dental restorations with spectral domain and polarization sensitive optical coherence tomography

Abstract: Restoration loss based on interfacial adhesive defects and associated caries at the restoration margin are the main causes for invasive replacement of dental restorations. Assessment of the interfacial quality based on clinical inspection and radiographic examination is often difficult and not reliable. In this work, we present spectral domain optical coherence tomography (SDOCT) and polarization sensitive optical coherence tomography (PSOCT) for the evaluation of tooth-composite bond failure. Imaging of two composite restorations at the occlusal surface are presented using intensity-based images obtained by SDOCT and PSOCT based degree of polarization uniformity (DOPU). Both modalities revealed several defects beneath the surface such as inhomogeneous adhesive layers, marginal gaps and bubbles. In addition, DOPU representation showed an inhomogeneous structure within the composite material. OCT based imaging of dental restorations could add a valuable diagnostic tool for the evaluation of structural defects in clinical practice. The representation of polarization characteristics with the DOPU algorithm provides further information on the homogeneity of the restoration.

Keywords: optical coherence tomography, dentistry, restoration, polarization, biomedical imaging

1 Introduction

Restoration defects such as marginal and internal interfacial gaps, micro-cracks and bubbles at the restoration-tooth interface are prominent predilection sites for the accumulation of plaque and bacteria. Since those micro-cavities are difficult to clean, the occurrence of caries at the restoration margin often leads to restoration replacement [1]. The detection of interfacial gaps and monitoring of their progression enables the dentist to implement early therapeutic strategies for the prevention of bacterial penetration. However, the detection and assessment of the dimension of interfacial defects by visual inspection is limited to larger defects apparent at the surface. Moreover, supplementary radiographic examination is not reliable for the validation of gap formation due to its poor resolution [2]. As a promising approach for the inspection of structural changes of dental hard tissues, optical coherence tomography (OCT) has become a prominent tool in dental research over the last recent years [3]. Based on its capability to provide depth-resolved, high resolution cross-sectional images and volume scans, OCT has been extensively used in cariology and restorative dentistry, particularly for the characterization of curious lesions [4]–[6]. Evaluation of restorations was performed previously with intensity-based OCT and correlated with light and scanning electron microscopic images as reference methods [7]. Due to the birefringent properties of enamel, co- and cross-polarized imaging with PSOCT has been applied to study changes in the polarization characteristics at curious lesions [8]. The degree of depolarization uniformity (DOPU) was first introduced for...
the assessment of depolarizing properties in ophthalmology [9]. The algorithm utilizes an averaging of adjacent speckles or pixels from the sub-resolution polarization scrambling of a depolarizing sample. In a recent studies, we have shown that the depolarization contrast of demineralized tissue represented by the DOPU contrast is a promising approach for the detection of early carious lesions [10] and in vivo imaging of the oral mucosa [11]. In this study, we introduce PSOCT for the assessment of interfacial adhesive defects at dental restorations and compare the DOPU based imaging with intensity-based SDOCT imaging.

2 Methods and setup

2.1 Preparation of Specimens

Two teeth with occlusal composite restorations (Class I, CeramX duo, Dentsply Sirona, Wals, Austria) were investigated (Fig. 1). The teeth were extracted in clinical routine at the University Hospital Leipzig and stored in 0.5 % chloramine solution at 4 °C to prevent dehydration. The restoration at tooth A was inserted using an adhesive (Scotchbond Universal, 3M Espe, Neuss, Germany, curing for 10 s) and was cured with LED based UV light (Bluephase, Ivoclar Vivadent, Schaan, Liechtenstein) for 30 s. In order to produce artificial interfacial gap formations at the tooth-restoration interface, no adhesive was used for tooth B.

2.2 Measurement setup

The presented OCT B-Scans were obtained at the position of the red dotted lines in Fig. 1. The teeth were imaged with a commercial SDOCT-system (TELESTO II, Thorlabs GmbH, Dachau, Germany). Recording parameter in vitro were: center wavelength 1310 nm, bandwidth 214 nm FWHM, sensitivity ≤ 106 dB, axial/lateral resolution < 7.5 (air)/15 µm, field of view maximum 8 mm x 8 mm x 3.5 mm (air, pixel size 800 x 400 x 1024), imaging speed 48 kHz, A-scan average 5.

PSOCT measurements were performed, using a custom polarization sensitive swept source OCT system [10]. Briefly, the system consists of a swept source laser (Axsun Technologies Inc., Billerica, Massachusetts) with a sweep rate of 50 kHz, and a center wavelength of 1310 nm, bandwidth 110 nm FWHM, axial/lateral resolution 15.1 (air)/15.6 µm, field of view maximum 10 mm x 10 mm and maximum imaging depth 4.96 mm with a lateral step size of 8 µm (air, pixel size 1280 x 1280) and a axial pixel size of 4.8 µm (air, pixel size 1024). Polarization characteristics were represented by the superposition of the calculated DOPU values within the color scale “Ametrine” [12] and the additional calculated reflectivity from the co- and cross-polarized channel of the system.

After OCT imaging, the teeth were sectioned through the regions of the red dotted lines (Fig. 1, corresponding B-Scans). Microscopic images (Fig. 2c, 3c) were obtained with reflected light microscopy, bright field, 0.63x (Stemi 2000-C, Carl Zeiss Microscopy GmbH, Jena) . For imaging of the specific composite region at Fig 2c1, transmitted light microscopy was used (20x, 0.5x Axioplan 1, Carl Zeiss, Oberkochen, Germany).

3 Results and Discussion

B-Scans of SDOCT and PSOCT (DOPU contrast) showed different defects at the restoration-tooth-interface at tooth A. In Fig. 2a and 2b the adhesive layer is clearly visible in the SDOCT image and DOPU representation as a layer with decreased intensity. The reflected light microscopy image confirms the adhesive layer at the area (Fig. 2c) but shows also that it does not pass around the complete restoration body. Adjacent to the adhesive layer, a bubble at the interface is visible (2) that is more pronounced in the SDOCT and PSOCT images (Fig. 2a, b). Although the contrast of the interfacial gap (3) is more obvious in the DOPU cross section, the dimension of the gap in the SDOCT corresponds more likely to the reference microscopic image. In addition to the visible defects at the restoration interface, the DOPU image reveals a coarse speckle pattern in the restoration body at both teeth (Fig. 2b, 4 and Fig. 3b, 3). The pattern can be interpreted as inhomogeneous polarization states and might be
Figure. 2: Cross sectional images at the position of the red dotted line of tooth A (Fig. 1A), obtained by SDOCT (a), DOPU representation (b), reflected bright field microscopy (c), and transmitted light microscopy (c1). Structures at the tooth-composite interface are visible: (1) adhesive layer of different thickness, (2) bubble at the interface, (3) interfacial gap, (4) inhomogeneous composite structure. C – composite restoration, E – enamel. The scale bars in a, b correspond to 500 µm.

Figure. 3: Cross sectional images at the position of the red dotted line of tooth B (Fig. 1B), obtained by SDOCT (a), DOPU representation (b), reflected bright field microscopy (c). Structures at the tooth-composite interface are visible: (1) interfacial gap, (2) large interfacial gap, (3) inhomogeneous composite structure. C – composite restoration, E – enamel. The scale bars in a, b correspond to 500 µm.
associated to the distribution of the filling agents in the composite material. The inhomogeneity is confirmed by transmitted light microscopy in Fig. 2c1. The gap formation at tooth B close to the surface layer (1) and the speckle pattern at the restoration body (3) show characteristics similar to tooth A. In contrast, the large interfacial gap is characterized by two high intensity layers at the boundary. Based on the dispense of an adhesive layer during sample preparation, it is to assume that this gap is a result of shrinkage during light curing. Overall, the findings of PSOCT based DOPU representation of composite restoration are in good agreement with SDOCT imaging. In terms of structural resolution, the DOPU contrast is limited to the applied kernel size (axial x lateral: 6 pixel x 6 pixel) for averaging of the derived Stokes components during PSOCT measurement (for further details, see [10]). This limitation is partially compensated by the superposition of the DOPU contrast with the reflectivity image, calculated from the co- and cross-polarization channel. On the other hand, DOPU representations provided additional information about the inhomogeneous polarization pattern at the restoration body that were not visible in the SDOCT B-Scan and in the reflected light microscopy images but were confirmed using transmitted light microscopy.

4 Conclusion

In this work, we presented SDOCT and PSOCT for the visualization of interfacial defects of composite fillings and compared the DOPU representation of cross sectional images with intensity-based SDOCT and light microscopy. All imaging modalities visualized several defects at the restoration-tooth interface. In addition, PSOCT revealed further information about the structural composition of the restoration that is associated with changes in depolarization properties. Future work will focus on the investigation of such characteristics at different restoration materials and their relation to mechanical properties.

Author Statement

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References