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Non-destructive characterization of voids in six flowable composites using swept-source optical coherence tomography

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ABSTRACT

Objective. The aim of this study was to evaluate the void frequency (V_F) and void volume (V_V) in different flowable composites using swept-source optical coherence tomography (SS-OCT).

Methods. Standard class I cavities were prepared and filled with six different flowable composites: Clearfil Majesty LV (MJ; Kuraray), MI Flow (MW; GC), MI Fil (ML; GC), Beautifil flow plus (BF; Shofu), Palfique Estelite low flow (EL; Tokuyama) and Surefil SDR flow (SF; Dentsply). The restorations were scanned under OCT. The OCT tomograms were analyzed and average V_F and V_V per restoration for each composite were calculated. Scanning electron microscope (SEM) was used to observe the structure of each composite. In addition, the flowability of the materials was evaluated measuring the displacement of each material placed up-right on a glass slide. V_F and V_V obtained by OCT were also compared to those calculated using micro-computed tomography (micro-CT).

Results. Kruskal–Wallis ANOVA and Mann–Whitney *U* tests revealed significantly different V_F and V_V values ($p < 0.05$) among the composites. Voids ranging from 35 to 785 μm in diameter were detected in OCT tomograms. MJ showed highest V_F and V_V values followed by MW, but ML, BF, EL and SF showed no significant difference. Filler volume in composites showed a positive correlation with void formation, but flowability did not show a specific trend. Micro-CT evaluation validated the V_F and V_V calculation by OCT, with a significant correlation in void size ($p < 0.001$, $r = 0.94$).

Conclusion. The results of this study indicate the reliability of SS-OCT for real-time void characterization of composite materials and restorations. Void formation in flowable composites is material dependent.

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1. Introduction

Defects such as voids and bubbles, which are essentially formed by entrapment of air within the materials, have shown to be detrimental to the mechanical properties of resin composites, particularly under fatigue loading [1,2]. Within the last decades, advanced composite resin materials have been developed with a focus on high mechanical properties and excellent esthetic. However, the fatigue behavior of composite resins has not shown a correlation with their initial strength values [3]. Fracture analysis has identified voids as critical defects where cracks nucleate under fatigue loading [4]. It is also reported that initial stress concentration around voids will lower the fatigue resistance [5], increase the wear, and finally lower the durability and performance of the restorations [6]. Accordingly, clinical data indicate that bulk fracture and chipping of the composite restorations are major contributors in clinical failure of composite restorations, which are attributed to the fatigue behavior of the composite materials [2,7]. Moreover, voids at the margins may lead to gross microleakage and discoloration [6]. Voids between the successive increments of resin composite have adverse effects on the flexural strength of the material [8], and voids on the surface of the restoration may require extra chair-side time to be removed. In addition, voids may be misinterpreted as secondary caries due to their radiolucent nature in X-ray radio graphs [9].

A number of methods have been used in order to assess defects in composite materials. Cutting the sample and observing it under microscope is the most basic destructive method [6]. On the other hand, methods that do not require cutting the sample are ultrasonic techniques, X-ray radiography, and micro-computed tomography (micro-CT) [10–12]. A more recent imaging technique is optical coherence tomography (OCT) [13]. The unique features of this safe technology enable a broad range of research and clinical applications [14].

OCT is a fundamentally new type of nondestructive and noninvasive optical imaging modality which uses the principle of low coherence interferometry to provide real time 1D depth, 2D cross-sectional and 3D volumetric images with μm level resolution and mm level of imaging depth [14,15]. OCT applies near infra-red (NIR) radiation to cross-sectionally scan the scattering medium. Images are reconstructed by measuring the backscattered or back reflected light [14]. The OCT technology has improved during the last decade, and swept-source OCT (SS-OCT) is one of the latest OCT systems with improved signal-to-noise ratio and scanning speed [16]. This system is capable of real-time 2D and 3D scanning [17–19]. In the dental field, the potential of OCT has been explored for oral tissue characterization [13,20], dental caries assessment [21,22], and interface evaluation of composite restorations [18,19]. The technology has a great potential for comparative assessment of light-scattering structures such as dental composites [23,24]. However, to our knowledge, there is no previous record on quantitative evaluation of voids within composites using OCT.

Therefore, the aims of this study were to apply SS-OCT to non-destructively determine the void frequency (V_F) and void volume (V_V) in different flowable composites, and to validate findings by micro-CT. The null hypothesis stated that V_F and V_V values were not significantly different among the tested composites bulk placed in class I cavities.

2. Experimental

2.1. Materials and sample preparation

Thirty extracted bovine incisors were selected for this study. Box formed cavities with round internal line angles 4 mm in diameter and 2 mm in depth were prepared on the flattened labial surfaces using high speed hand piece and round diamond bur (Shofu, Kyoto, Japan). The specimens were randomly distributed among six groups based on the flowable composites used for filling ($n = 5$). After applying a dental adhesive (Clearfil SE Bond; Kuraray Medical, Japan) according to the manufacturer's instructions, each composite resin was injected into the cavity. The composite materials used and their compositions are listed in Table 1.

2.2. SS-OCT system and tomographic procedure

The SS-OCT system used in the present study (IVS-2000, Santec, Komaki, Japan) was a frequency domain OCT with 100 nm bandwidth, centered at 1310 nm spectra at 20 kHz scan rate. The sensitivity of the current OCT system is 106 dB, whilst the shot-noise limited sensitivity is 119 dB. The system incorporated a hand-held probe with a power less than 20 mW. The axial resolution of this system is 11 μm in air, equivalent to approximately 7 μm in oral hard tissue structures and resin composites (assuming a refractive index of around $n = 1.5$), and the lateral resolution is about 17 μm [19,23].

The laser light beam is projected from the probe onto the sample, cross-sectionally scanning the selected area. Backscattered light is collected and digitized in time scale and analyzed in the Fourier domain to reveal the depth-resolved reflectivity profile (A-scan) at each location. The combination of a series of A-scans along a scan path creates a B-scan. B-scans contain the signal intensity value (dB) of each point on the x and z axes. By converting the B-scan raw data into gray-scale, a 2D cross-sectional image can be created. This system is capable of 3D acquisition of data from the structure by serial B-scans over an area.

All the composites were carefully filled into the cavities at room temperature by the same operator following the same placement technique. During injection of the composite into the cavity, the nozzle tip was constantly held away from the dispensed composite. After placing of each composite material into the prepared cavity and irradiation with a halogen light curing unit (Optilux 501, Kerr, Orange, CA, USA) according to the instructions in Table 1. The specimens were then cross-sectionally scanned with SS-OCT. 3D scans were performed over a volume of interest of 5 mm × 5 mm × 5 mm centered at the cavity obtained in the form of 300 serial sagittal B-scans at a resolution of 760 × 430 pixels (x, z).