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Early resin luting material damage around a circular fiber post in a root canal treated premolar by using micro-computerized tomographic and finite element sub-modeling analyses

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ABSTRACT

This study utilizes micro-computerized tomographic (micro-CT) and finite element (FE) sub-modeling analyses to investigate the micro-mechanical behavior associated with voids/bubbles stress behavior at the luting material layer to understand the early damage in a root canal treated premolar. 3-dimensional finite element (FE) models of a macro-root canal treated premolar and two sub-models at the luting material layer to provide the void/bubble distribution and dimensions were constructed from micro-CT images and simulated to receive axial and lateral forces. The boundary conditions for the sub-models were determined from the macro-premolar model results and applied in sub-modeling analysis. The first principal stresses for the dentin, luting material layer and post in macro-premolar model and for luting material void/bubble in sub-models were recorded. The simulated results revealed that the macro-premolar model dramatically underestimated the luting material stress because the voids/bubbles at the adhesive layer cannot be captured due to coarse mesh and high stress gradient and the variations between sub- and macro-models ranging from 2.65 to 4.5 folds under lateral load at the mapping location. Stress concentrations were found at the edge of the voids/bubbles and values over 20 MPa in sub-modeling analysis immediately caused the luting material failure/micro-crack. This study establishes that micro-CT and FE sub-modeling techniques can be used to simulate the stress pattern at the micro-scale luting material layer in a root canal treated premolar, suggesting that attention must be paid to resin luting material initial failure/debonding when large voids/bubbles are generated during luting procedures.

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1. Introduction

The use of fiber posts in the reconstruction of endodontically treated teeth has increased in popularity. The major advantage of fiber posts is their similar elastic modulus to dentine, producing a stress field similar to that of natural teeth, whereas metal posts exhibit high stress concentrations at the post-dentine interface (Aksornmuang et al., 2004). Some researchers have reported that using a fiber post could reduce the incidence of root fractures (Mannocci et al., 1999, 6; Ferrari et al., 2000a, 2000b, 5; Akkayan and Gülmez, 2002). In vitro experimental study showed that used with fiber-reinforced composite posts the failures may more often be favorable compared to titanium posts, which clinically means repairable failures (Le Bell-Rönnlöf et al., 2011). Clinical studies have also demonstrated high success rates without the occurrence of root fractures (Ferrari et al., 2000a, 2000b).

The most frequent cause of failure in teeth reconstructed with fiber posts is not root fracture but post-debonding, which can occur at the post-cement (resin luting material) interface and/or between cement and root dentin (Prisco et al., 2003; Aksornmuang et al., 2004; Rengo et al., 2014). Debonding may be due to several factors, post-surface treatments, dentin bonding agents and cements, adhesive application and polymerization mode (Sahafi et al., 2004; Faria e Silva et al., 2007; Monticelli et al., 2008). As a consequence of cement application technique and polymerization shrinkage a number of gaps, voids and bubbles are observed within the luting material interface (Bouillaguet et al., 2003; Grandini et al., 2005; Bolhuis et al., 2005; Watzke et al., 2008). All of these imperfections reduce the ability of a luting material to sufficiently adhere to the post-surface and retain the endodontic post (Bachicha et al., 1998; Reid et al., 2003). Air bubbles or voids within the luting material interface could be incorporated and induce stress concentration to induce micro-leakage, predisposing the post to debonding (Grandini et al., 2005). Although many authors investigated the influence of cement thickness on the bond strength of fiber posts (Perez et al., 2006; da Rosa et al., 2011; Egilmez et al., 2013), there is no agreement in the literature on the ideal cement thickness, as well as on the influence of voids (gaps, air bubbles, emptiness within the cement layer, or at the post/cement and cavity wall/cement interfaces) on the fiber post-bond strength and the clinical outcome. Therefore, information on the micro-mechanical mechanisms related to air voids/bubbles within the resin luting material (cement) associated with stress concentration at the adhesive layer is required to reduce the risk for interface debonding.

The typical finite element (FE) approach to obtaining detailed mechanical information on, and thus to model, the adhesive bonded interface between luting material and post or luting material and dentin is difficult (Zarone et al., 2005; Soares et al., 2008). The difficulty arises from the fact that the voids/bubbles dimensions are much smaller than those of the global configuration. Hence, sub-modeling has an advantage over the typical FE approach in that it uses a local micro-model with boundary conditions that are based on the pre-analyzed global model results to determine the local mechanical responses. This approach can be employed to investigate the mechanical behavior of the adhesive phase (Gupta et al., 2004; Liu et al., 2009; Lin et al., 2011). Moreover, a nondestructive analysis using micro-computerized tomography (micro-CT) can be used for a three-dimensional (3D) analysis of the tooth, post-space volumes and void/bubble morphology to generate an accurate 3D reconstructed FE model (Grande et al., 2008).

The aim of this study is to utilize the micro-CT image processing with FE sub-modeling to investigate the micro-mechanical behavior associated with voids/bubbles stress behavior at the luting material (cement) layer to understand the early distribution of luting material damage in a root canal treated tooth.

2. Materials and methods

2.1. *Root canal treated tooth macro-model generation and analysis*

A freshly extracted intact maxillary upper second premolar was embedded and scanned with micro-CT (Skyscan, Aartselaar, Belgium). All micro-CT image files were processed using commercially available software (Amira, v4.1; Mercury Computer Systems, Inc., Chelmsford, MA) that allowed the different hard tissues (enamel, dentin, and pulp) to be identified to generate solid models in the FE program (ANSYS, v13.0; Swanson Analysis Inc., Houston, PA, USA). A solid model with intact maxillary premolar and simplified bone segment was then assembled with 0.25-mm periodontal ligament (PDL). Preparation designs were generated using a parametric cutting plane replaced with adhesive CAD/CAM ceramic crown built up onto a fiber post (1.3 mm in diameter and 13 mm in length) and composite core unit (Fig. 1(a)). All solid models for the intact and root canal treated teeth were derived from a single mesh pattern.

A convergence test was used to verify the FE analysis results and guarantee that our numerical model reached the converged results and that no further mesh refinement was necessary. It was performed using different mesh models to control the strain energy and displacement variations to less than 5%. The exterior nodes at the mesial, distal and bottom surfaces of the alveolar bone were fixed in all directions as the boundary conditions for all models. The axial load was applied on the tooth at two points on the cusps with the resulting force crossing the central position was 200 N (Fig. 1(a)). The load application points and directions were modeled in accordance with a load test set-up following a validated experimental protocol (Fig. 2). Linear and elastic enamel, dentin, pulp and epoxy resin (instead of PDL and alveolar bone) material properties were assigned according to the volume definition from the literature (see Table 1). After the convergence test, the resulting 3D FE model was meshed with 607,890 linear structural solid elements and 817,765 nodes (Fig. 3(a)). To validate our premolar FE model, five freshly extracted intact maxillary second premolars were cleaned to strip ligaments and any residual tissue and subsequently embedded from the root to 1-mm below the CEJ into an epoxy resin block (Truetime Industrial Co., Taiwan). Two strain gages (Kyowa, Electronic Instruments