Estimation of the Failure Risk of a Maxillary Premolar with Different Crack Depths with Endodontic Treatment by Computer-aided Design/Computer-aided Manufacturing Ceramic Restorations

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Abstract

Introduction: This study evaluated the risk of failure for an endodontically treated premolar with different crack depths, which was shearing toward the pulp chamber and was restored by using 3 different computer-aided design/computer-aided manufacturing ceramic restoration configurations. **Methods:** Three 3-dimensional finite element models designed with computer-aided design/computer-aided manufacturing ceramic onlay, endocrown, and conventional crown restorations were constructed to perform simulations. The Weibull function was incorporated with finite element analysis to calculate the long-term failure probability relative to different load conditions. **Results:** The results indicated that the stress values on the enamel, dentin, and luting cement for endocrown restorations exhibited the lowest values relative to the other 2 restoration methods. Weibull analysis revealed that the overall failure probabilities in a shallow cracked premolar were 27%, 2%, and 1% for the onlay, endocrown, and conventional crown restorations, respectively, in the normal occlusal condition. The corresponding values were 70%, 10%, and 2% for the depth cracked premolar. **Conclusions:** This numeric investigation suggests that the endocrown provides sufficient fracture resistance only in a shallow cracked premolar with endodontic treatment. The conventional crown treatment can immobilize the premolar for different cracked depths with lower failure risk. *(J Endod 2013;39:375–379)*

Key Words

Cracked tooth, endodontically treated premolar, failure probability, finite element analysis, Weibull analysis

A cracked tooth is described as having a crack that extends from the centered occlusal surface of the tooth apically without separation of the 2 segments and is more likely to cause pulpal and periradicular pathosis (1, 2). Cracked tooth occurs most commonly in mandibular molars, followed by maxillary premolars (3–6). The crack may cross one or both marginal ridges and is most often mesiodistal, shearing toward the lingual root surface.

The cracked tooth treatment plan varies depending on the location and extent of the crack. Even when the crack can be located, the extent is still difficult to determine. Ailor (7) presented a flow chart that took into consideration the pulp status at the time of crack discovery. He suggested temporizing the tooth with a temporary crown and monitoring it for symptoms. Opdam et al (8) indicated that a direct bonded composite resin restoration can be a successful treatment for a painful cracked tooth including reversible pulpitis. Krell and Rivera (6) found that if a marginal ridge crack is identified early enough in teeth with a diagnosis of reversible pulpitis and a crown is placed, root canal treatment will be necessary in about 20% of patients within 6 months. However, endodontic treatment is often indicated, followed by a full crown to bind the cracked segments and protect the cusps (1).

When the pulpal and periradicular status dictates treatment, the longevity of endondontic treatment is significantly influenced by the type of restorative materials used with the appropriate restoration that conserves tooth structure (9, 10). The quality and integrity of the remaining tooth must be preserved with caution because it provides the solid base required for tooth restoration and influences the structural strength of the restored tooth (11, 12). In recent years, innovative computer-aided design/computer-aided manufacturing (CAD/CAM) technology has added a new dimension for chair-side ceramic restorations to repair large tooth cavities. All-ceramic crown restorations have been used as an alternative to metal crowns for tooth reconstruction (9, 12–14). In particular, the CAD/CAM endocrown can be built from a single block of ceramic including a radicular portion and a ceramic-coated core (15). Several clinical case reports and biomechanical studies have shown the potential of this restorative approach to provide adequate function and esthetics (9, 15–19). However, there is no clear recommendation about which technique can optimally restore a cracked maxillary premolar, which is more prone to fracture after restoration (20).

Weibull analysis has frequently been used to calculate the probability for fracture in brittle materials. It has also provided a method for combining with the finite element (FE) method to predict cumulative failure probability at selected stress levels

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in our previous risk of failure estimation studies (9). The aim of this study therefore was to compare the stress distribution patterns and risks for failure by using both FE and Weibull analyses for a maxillary premolar with different crack depths, shearing toward the pulp chamber and restored by using CAD/CAM ceramic restorations with onlay, endocrown, and crown built up onto a metal post-core unit.

Materials and Methods

FE Model Generation and Validation

A cadaver left maxilla that was edentulous in the second premolar was scanned by using computed tomography (CT) image to construct the FE bone model. A freshly extracted intact maxillary upper second premolar was embedded and scanned with high-resolution micro-CT (Skyscan, Aartselaar, Belgium) with a voxel dimension of 35 μm. All CT and cross-sectional micro-CT image files were processed by using commercially available software (Amira, v4.1; Mercury Computer Systems, Inc, Chelmsford, MA) that allowed the different hard tissues (cortical bone, cancellous bone, enamel, dentin, and pulp) to be identified to generate solid models in FE program (ANSYS, v11.0; Swanson Analysis Inc, Houston, PA). A solid model with tooth and bone segment was then assembled with a simplified 0.25-mm periodontal ligament.

The premolar was designed as a crack across mesial marginal ridge that sheared toward the pulp chamber. Two crack depths were assumed with both from the occlusal surface; one extended to above bone (AB) level about 1 mm, and the other was below bone (BB) level extent to the mid-root location. Preparation designs were generated by using a parametric cutting plane replacing with adhesive CAD/CAM ceramic onlay, endocrown, and crown built up onto a metal post and composite core unit (Fig. 1*A* and *B*).

All solid models for the different restorations were derived from a single mesh pattern. A convergence test was performed in different mesh models to control the strain energy and displacement variations to less than 5%. The resulting 3-dimensional FE model was meshed with 134,810 linear 8-node structural solid elements and 187,241 nodes (Fig. 1*C*). A parallel *in vitro* compressive experiment for 4 intact teeth was performed to validate the static FE analysis results of intact tooth model. The validated results showed that the comparison between the experimentally measured and numerically calculated strains were within 18% error (FE analysis, -48.74 μm; strain gauge, -54.49 ± 13.72 μm) and indicated that our premolar FE model was reasonable for further simulations.

FE and Weibull Analyses

The linear elastic, homogeneous, and isotropic material properties of all simulated materials were assigned according to the volume definition from the literature (Table 1). The perfect bonded condition was used to model the interfacial adaptation between the cement and tooth and cement and restorative material (ceramic). The crack interface was modeled by using nonlinear frictional contact elements (assumed a friction coefficient of 0.5) to simulate the crack interfacial adaptation for all simulations. The exterior nodes of the bone block were fixed in all directions as the boundary conditions. The load was applied on the tooth with buccal and lingual cusp contact (the same position in model validated experiment) for simulating the axial load, with the resulting force crossing the central position at 100–2000 N (100-N increments). Forty nonlinear contact FE models were constructed with 2 crack depths and 20 loads in our simulation. The normal stress failure criterion was assumed, with failure presumed to occur from the highest principal tensile stress on stress concentration areas. Weibull risk-of-rupture analysis was used, in which the survival probability, P_s, is given as the following (21–23):

$$P_s(\sigma) = -\exp\left[-\left(\frac{\sigma}{\sigma_0}\right)^m\right] \qquad \text{(Equation 1)}$$

where P_s represents the survival probability of node at stress σ (for load F), σ represents the failure stress, σ_0 represents the characteristic strength, and m represents the Weibull modulus, which is a material parameter. When loaded, a restoration will survive until the risk of rupture reaches a critical value at any one of the multiple failure sources. Hence, for a system of n = i sources, the overall survival probability, P_s, is the product of the individual survival probabilities:

$$P_s = \prod\nolimits_i P_{si} \qquad \text{(Equation 2)}$$

where i = 1, 2, 3, 4 in the case of the crack premolar with different restorations, because the stress concentration regions of the enamel, dentin, cement, and ceramic were observed at risk. Hence, the failure probability, P_f, for the total system is calculated by using the following formula:

$$P_f = 1 - (P_{S1} \times P_{S2} \times P_{S3} \times P_{S4}) \qquad \text{(Equation 3)}$$

Probability of failure versus load curves was calculated; characteristic strengths (σ_0) and Weibull modulus (m) for different materials were adopted for calculation from the literature and test data (Table 1).

Results

The stress values on the enamel, dentin, and luting cement for onlay restoration were found as the highest values in different crack depth teeth compared with the corresponding values for endocrown and conventional crown restorations (Table 1). However, the stress values on the dentin and luting cement in the endocrown restoration were found to be lower than those for the conventional crown restoration.

The stress pattern results showed that the onlay restoration presented obvious stress concentrations compared with endocrown and conventional crown restorations (Fig. 1*D*). The stress concentration regions in the enamel and dentin in onlay restorations were found at the crack line on the pulpal floor for different crack depths (Fig. 1*D*). The cement high stress region was also noted at the sharp corner in the onlay configuration (Fig. 1*D*).

Long-term failure probability in relation to varying load conditions in the 3 restoration configurations at different crack depths were calculated and are shown in Figure 2. Generally, the failure risks of the BB crack tooth were higher than those for the AB crack tooth, regardless of onlay, endocrown, or crown restoration under the same occlusal load condition. A large variation in failure probability was found with the endocrown restoration between the AB and BB crack tooth situations when the occlusal load was higher than 250 N.

Discussion

Root canal treatment followed by a full crown restoration is recommended by the American Association of Endodontists when the radiographic examination indicates a periapical lesion, or if the patient presents with a history of lingering cold sensitivity, heat-induced pain, throbbing, or spontaneous pain, irreversible pulpitis is indicated (1, 24). Nevertheless, the classic treatment option would be a custom-made conventional crown; however, loss of sound tooth structure and compromised bonding strength might increase the risk of crown restoration failure. A conservative approach by using esthetic CAD/CAM ceramic restoration with single appointment can be advantageous for the patient because it eliminates many of the steps involved in