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Effect of damping properties on fracture resistance of root filled premolar teeth: a dynamic finite element analysis

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Abstract

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Aim To evaluate the *ex vivo* effects of damping on stress concentration in root filled premolar teeth.

Methodology Damping ratios of maxillary premolar teeth that had undergone root canal treatment were tested in a laboratory model. In addition, two-dimensional finite element (FE) models were established for dynamic analysis.

Results The mean-damping ratio was significantly lower in premolar teeth that had undergone root canal preparation (8.50 ± 0.53%) than in unprepared teeth (14.42 ± 2.17%) ($P < 0.05$). However, root filling had a significant positive effect on the damping ratio of the tooth (10.84 ± 1.70%) ($P < 0.05$). When the damping ratio was taken into consideration, FE analysis revealed that peak stresses in the apical one-third of the root on the buccal side were reduced by 31.8% when mastication forces were applied on the palatal cusp and occlusal fossa.

Conclusion Pulp tissue plays an important role in providing protective effects when teeth are subjected to a dynamic load. However, root filled teeth do not provide such protective effects.

Keywords: damping ratio, dynamic finite element, premolar, stress.

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Introduction

It has been reported that root canal treatment reduces the strength of teeth and increases the risk of tooth fracture (Akkayan *et al.* 2002, Hannig *et al.* 2005, Sathorn *et al.* 2005, Soares *et al.* 2008). It is well known that stress distribution in dentine is the major factor leading to tooth fracture. Therefore, reducing the induced strain in a loaded tooth is the best strategy for diminishing the damage of a tooth subjected to sudden loading. It has been reported that the strength of root filled teeth is dependent on the amount of tooth structure that remains after treatment (Sirimai *et al.* 1999, Hurmuzlu *et al.* 2003). However, a previous study has demonstrated that there are no significant changes in the hardness or modulus of elasticity of root filled teeth (Larson *et al.* 1981). Therefore, there must be other factors related to fracture resistance of teeth that have undergone root canal treatment.

Transmission of strain within a tooth has been reported to be dependent on its shape, composition and elastic properties (Magne & Belser 2003, Soares *et al.* 2008). However, a tooth is viscoelastic because it contains several types of organic fluids and soft tissues. From a mechanical viewpoint, the damping materials should act as shock absorbers minimizing the strain because of external impact. Recently, Huang *et al.*

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(2006) showed for the first time that the damping properties could protect the tooth during traumatic injury by decreasing the peak stress caused by the release of strain energy over a longer period.

Although the damping properties of the periodontal ligament (PDL) are the main contributors to the viscoelastic property of a tooth clinically; the cushioning effect of other damping materials, such as the pulp, could affect the stress distribution during an impact (Huang *et al.* 2005). It is known that soft tissue loss will greatly reduce the viscous properties of teeth, and that root filled teeth are more susceptible to fracture (Sathorn *et al.* 2005, Soares *et al.* 2008); however, the effects of root canal treatment on the viscoelastic properties of teeth have not been reported.

Many studies have investigated the fracture resistance of root filled teeth when a monotonic load is applied (Al-Ali *et al.* 2003, Reid *et al.* 2003). However, mastication forces are dynamic, the magnitude of which is variable at different times (Salis *et al.* 1986). The clinical significance of the results from a monotonic analysis is questionable, not only because a monotonic load does not represent the clinical occlusal loads (Goto *et al.* 2005, Qing *et al.* 2007), but also the stress responses to dynamic and static loads are different. Static analysis ignores the stress-damping effect of the soft tissues, thereby causing an unexpected error.

No studies have investigated the relationship between stress concentration in the tooth root and the damping properties of root filled teeth. Therefore, in this study, dynamic finite element analysis (FEA) was used to investigate stress concentrations in root filled teeth under dynamic occlusal loads.

Material and method

In vitro modal testing

To investigate the effect of endodontic treatment on the damping factor values of maxillary premolars, five extracted single-rooted maxillary premolars, free of cervical and root cracks, fractures and caries were collected from the Taipei Medical University Hospital for use in the laboratory model, as was described in a previous study (Wang *et al.* 2008).

The premolars were tested in three stages. In stage I, the unprepared teeth were fixed on the buccal and palatal sides by a metal clamp stand with a torque force of 20 N cm. In stage II, the teeth underwent canal cleaning and shaping treatment. Briefly, serial instrumentation of the root canals was performed with a FlexoFile® (Dentsply Maillefer, Ballaigues, Switzerland). The apical portion of the canal was prepared up to a 30 file and step-back flaring was accomplished to produce a 0.05 taper. The teeth were then restored with a provisional restorative material (IRM®; Dentsply). In stage III, the provisional restorative material was removed, and the root canals were filled with gutta-percha and an endodontic sealer by a standard vertical compaction procedure. Finally, the premolars were restored with the same provisional restorative material. Laboratory modal testing was performed on the test samples during each stage. During the test, teeth were moist at room temperature using saline solution. Sodium hypochlorite (NaOCl) was repeatedly used for irrigation during canal instrumentation and prior to the laboratory tests.

During modal testing, the teeth were vibrated by a transient force using an impulse force hammer (GK291C80; PCB Piezotronics, Buffalo, NY, USA). The vibration signal was recorded by a noncontacting acoustic microphone (FM-10B, sensitivity 20 kHz; FC Electronics, Taipei, Taiwan). The recorded signals were then transferred into a personal computer through an A/D interface card (AD102 A; Prowave Engineering, Hsinchu, Taiwan). FFT software (SD200N, Signal Doctor; Prowave Engineering) was then used to determine the resonance frequency of the teeth (Fig. 1). The damping ratio (ξ) and resonance frequency of each of the premolar samples were obtained by detecting the amplitude decay trend and vibration frequency of the

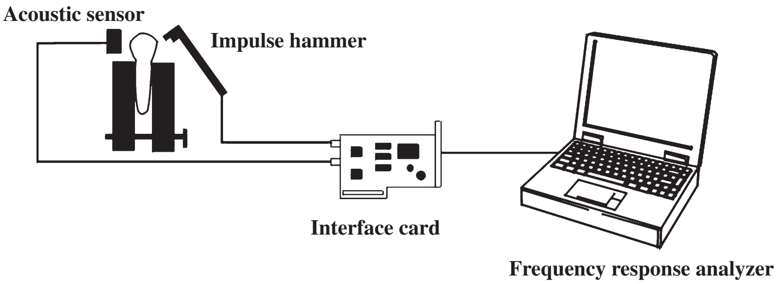

Figure 1 Schematic diagram of the *in vitro* modal testing experiment.

vibrating tooth respectively (Huang *et al.* 2006). One-way analysis of variance and the Tukey *post hoc* test were computed to test the variation of the damping ratio values. In addition, to obtain the resonance frequency and damping ratio values of alveolar bone, Laboratory tests were also performed on seven cadaver alveolar bones obtained from the Oral and Maxillofacial Physiology Laboratory, Taipei Medical University, Taipei, Taiwan as previously reported (Lin *et al.* 2006).

In vivo modal testing experiment

To validate the FE model, the resonance frequency of maxillary premolars was tested *in vivo* using a dental implant stability detection device (Implomates System; Biotech One, Taipei, Taiwan), as was described previously (Chang *et al.* 2007). The measured data were then used to validate the FE model. A total of 16 maxillary premolars from eight periodontally healthy (probing depth ≤3 mm), young adults (20–25 years) were subjected to the *in vivo* tests. Resonance frequencies were determined from the relative maximum of vibration amplitude on the frequency domain spectrum. Each tested tooth was tested five times.

Finite element model

As shown in Figure 2, three two-dimensional plane-strain FE models were built using FEA package (ANSYS®; Swanson Analysis System Inc., Houston, PA, USA). The geometry of the models was based on the X-ray images of one extracted premolar used in the laboratory studies, when the canal was unprepared (model I), when the canal was prepared (model II) and then were filled (model III). The geometry and dimensions of the surrounding tissue of the premolar, including the 0.25 mm thickness of the periodontal membrane, was selected as in a previous study (Lee

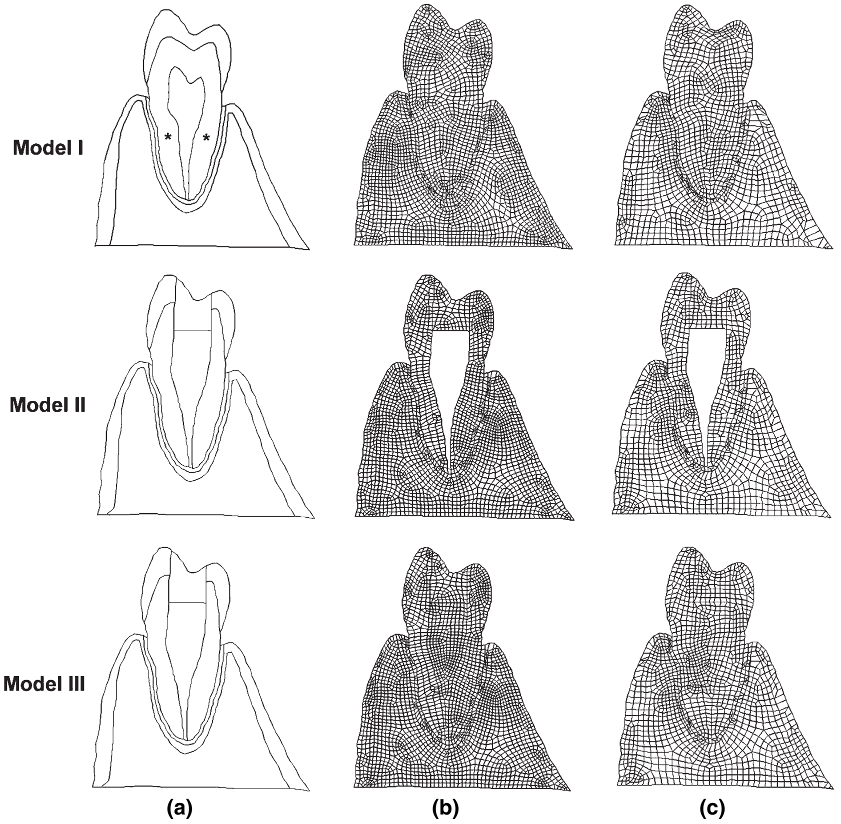

Figure 2 Two-dimensional solid models (a) and plane strain finite element (FE) models of the human maxillary premolar meshed with 0.6 mm (b) and 0.9 mm (c) element sizes. Models I, II, III represent unprepared premolars, premolars that received endodontic cleaning and shaping treatment and those that received root canal filling respectively. * denote locations where equivalent stress was computed for comparison.

Table 1 Material properties used in the finite element (FE) model

	Young's modulus (GPa)	Poisson's ratio	References
Enamel	84.10	0.33	Kampoosiora *et al.* 1994
Dentin	18.30	0.31	Kampoosiora *et al.* 1994
Pulp	2.07×10^{-3}	0.45	Kampoosiora *et al.* 1994
PDL	68.90×10^{-3}	0.45	Kampoosiora *et al.* 1994
Cortical bone	10.00	0.30	Kampoosiora *et al.* 1994
Cancellus bone	0.25	0.30	Kampoosiora *et al.* 1994
Restorative material	3.00	0.24	Lakes 2002
Gutta-percha	9.30×10^{-4}	0.40	Lakes 2002

PDL, periodontal ligament.

et al. 2000). The material properties (Table 1) of the models were obtained from those reported in the literature (Kampoosiora *et al.* 1994, Lakes 2002). All interfaces between different materials were assumed to be in perfect bonding.

In dynamic FE analyses, the structural-damping factor (β) is an essential input parameter. The structural-damping factor of premolars can be derived according to the following formula (Huang *et al.* 2005):

$$\beta = \frac{\xi}{\pi f} \qquad (1)$$

where ξ is the damping ratio, and f is the first resonance frequency of the maxillary premolar. In this study, the structural-damping factors of teeth and surrounding bone were calculated from the laboratory experimental data. The structural-damping factor of the periodontal membrane was assumed to the same as that of the ligament with a value of 1×10^{-4} (Sun *et al.* 2002). All the data are represented as mean ± standard deviation (SD).

To test the convergence of the FE models and to choose an adequate mesh density, the solid model of the unprepared premolar was meshed with various element sizes, ranging from 0.5 mm to 0.9 mm in 0.1 mm steps (Fig. 2). The criterion of convergence was a less than 1% variation in computed results. The resonance frequencies of these unprepared premolar models were then calculated and the frequencies were compared with those derived from the *in vivo* modal testing experiment.

Transient dynamic finite element analysis

A personal computer was used to perform the transient dynamic analyses of the three premolar models described above in order to test the effect of damping properties on the stress concentration of maxillary premolars subjected to a dynamic load. To simulate dynamic mastication forces, sinusoidal forces with a peak of 300 N (Craig & Powers 2002) at 2 ms, and a total duration of 4 ms (Huang *et al.* 2005) were applied to the tooth along the long axis of the root. In this study, three loading conditions were simulated. In the first and second conditions, the loads were applied on the occlusal fossa and palatal cusp (load I) (Dawson 2007) and occlusal fossa and buccal cusp (load II). In the third condition, the loads were applied on the buccal and palatal cupsal inclines (load III) (Fig. 3). In all of the simulations, FE models without damping property were treated as the control by setting the structural-damping factor to zero. Equivalent stress contours within the FE models were calculated and displayed for comparison. The stresses at the apical one-third of the root were plotted against time, and the stress-damping effects of the pulp were evaluated by comparing the peak stress values of the palatal side of the dental root with those of the buccal side of the root.

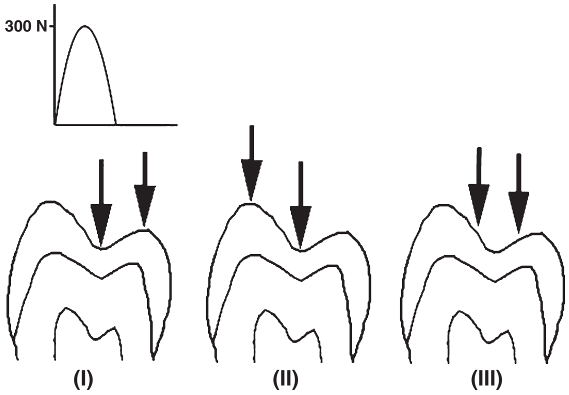

Figure 3 Loading conditions simulated in this study. Load I, II and III represent the situations that the loads were applied at the occlusal fossa and palatal cusp, occlusal fossa and buccal cusp, and at buccal and palatal cupsal inclines respectively.

Results

The measured damping ratios of the premolars at the three treatment stages are presented in Figure 4. Statistical analysis revealed that the mean-damping ratio was significantly lower in premolars that had undergone canal cleaning and shaping (8.50 ± 0.53%) than in unprepared premolars (14.42 ± 2.17%) ($P < 0.05$). However, root filling and provisional restorative material had a significantly positive effect on the recovery of the damping ratio value (10.84 ± 1.70%) ($P < 0.05$). The mean resonance frequencies of the premolars at the three treatment stages were 6270 Hz ± 452 Hz, 6846 ± 384 Hz and 5859 ± 527 Hz respectively. According to Equation (1), the structural-damping factors of the maxillary premolars were 0.73×10^{-5}, 0.40×10^{-5} and 0.59×10^{-5} in FE models I, II and III respectively. In addition, the mean resonance frequencies and damping ratios of the tested alveolar bone were 557 ± 47 Hz and 5.33 ± 0.38% respectively. Accordingly, the structural-damping factor of the alveolar bone assigned in the three FE models was 3.05×10^{-5}.

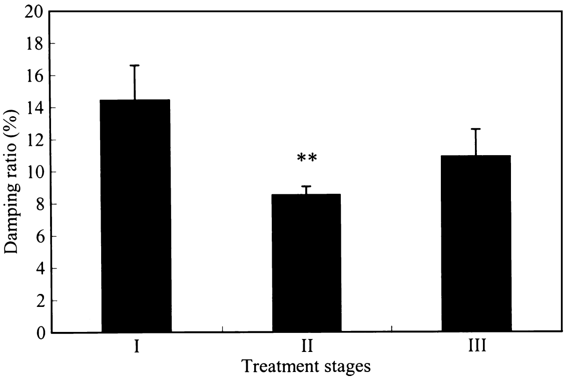

Figure 4 Measured damping rations of the extracted maxillary premolars under different treatment stages. Stages I, II, III represent unprepared premolars, premolars after endodontic cleaning and shaping treatment and premolars that received root canal filling respectively. ** denotes $P < 0.01$.

Table 2 Calculated resonance frequencies of the maxillary premolar FE models meshed with different densities

Element size (mm)	Element number	Resonance frequency (Hz)
0.9	1436	3138.3
0.8	1579	3131.5
0.7	1857	3131.5
0.6	2310	3131.6
0.5	3638	3123.8

When the unprepared maxillary premolar FE model was meshed with various element sizes (range, 0.5 mm–0.9 mm in 0.1 mm steps), the calculated resonance frequencies ranged from 3131.6 Hz to 3138.3 Hz (Table 2), values which were close to those obtained from the *in vivo* experiments 3100 ± 310 Hz. Considering the accuracy and convergence of the calculations, 0.6 mm was chosen as the element size for meshing all the FE models in the following numerical simulations.

Figure 5 demonstrated an example of the sequential stress contours in premolar models subjected to load I force. The concentrated stresses, at various locations inside the tooth, altered with time when dynamic analysis was used. In all three models, high stresses were concentrated at areas around the points at which the forces were applied and at the dental root around the cementoenamel junction (CEJ). The time points when maximum stress occurred were close to 2 ms for all three models. When comparing maximum stress contours (at 2 ms) in the models, under different loading conditions, the Load III situation induced similar stress patterns in the model, with the lowest peak values amongst the three. In the load II condition, no obvious stress concentration was found, except for the areas around the loading sites (Fig. 6).

When the stresses at the apical one-third of the root were plotted against time, the peak stresses on the palatal and buccal sides differed markedly. In the load I condition (Fig. 7), stresses on palatal root (excess of 80 kPa) were much greater than that on the buccal side for all the three premolar models. However, this phenomenon reversed when load II forces were used (Fig. 8). When applying load III forces, the stress-time curves were similar to load I condition, but with lower peak-stress values (Fig. 9).

The obvious effects of damping properties on peak stress values can be seen in the unprepared model (model I) for all three loading conditions. In the Load I condition (load applied to palatal cusp), the peak stress on the buccal root were markedly reduced by about 32% (from 47 kPa reduced to 32 kPa) when damping properties were taken into consideration. The reduction was only 12% (from 163 kPa to 143 kPa) on the palatal root (Fig. 7). By contrast, when the load was applied to the buccal cusp (load II condition), the stress reduction on the palatal root was 6% (from 55.9 kPa to 52.2 kPa). However, no obvious stress reduction can be seen on the buccal root. When loads were applied on

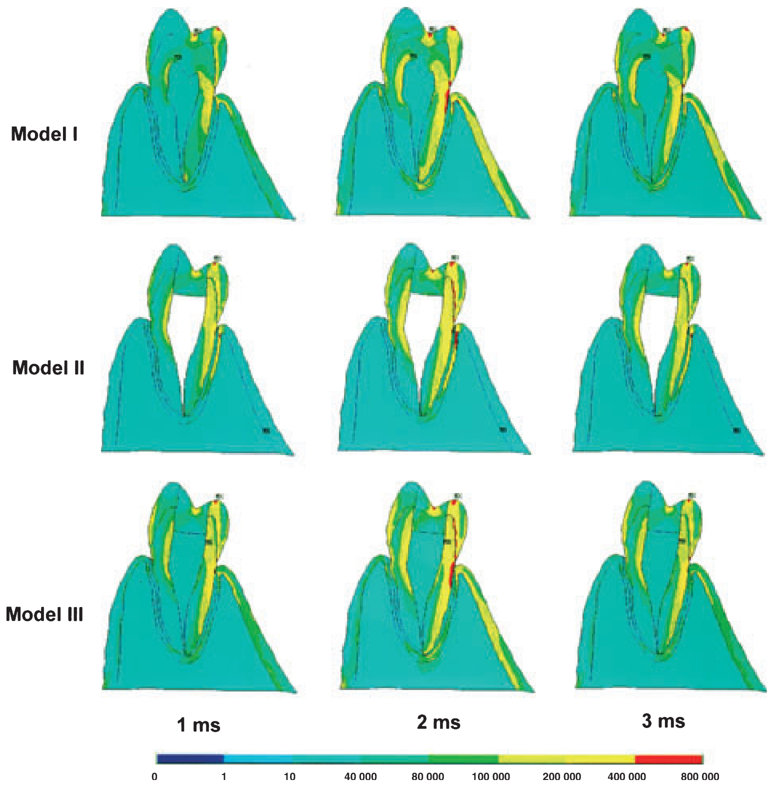

Figure 5 Equivalent stress distributions developed in the maxillary premolars at 1, 2 and 3 ms after the teeth were subjected to dynamic mastication forces. Models I, II, III represent the unprepared model, the cleaning and shaping treated model and the root canal filling treated model respectively.

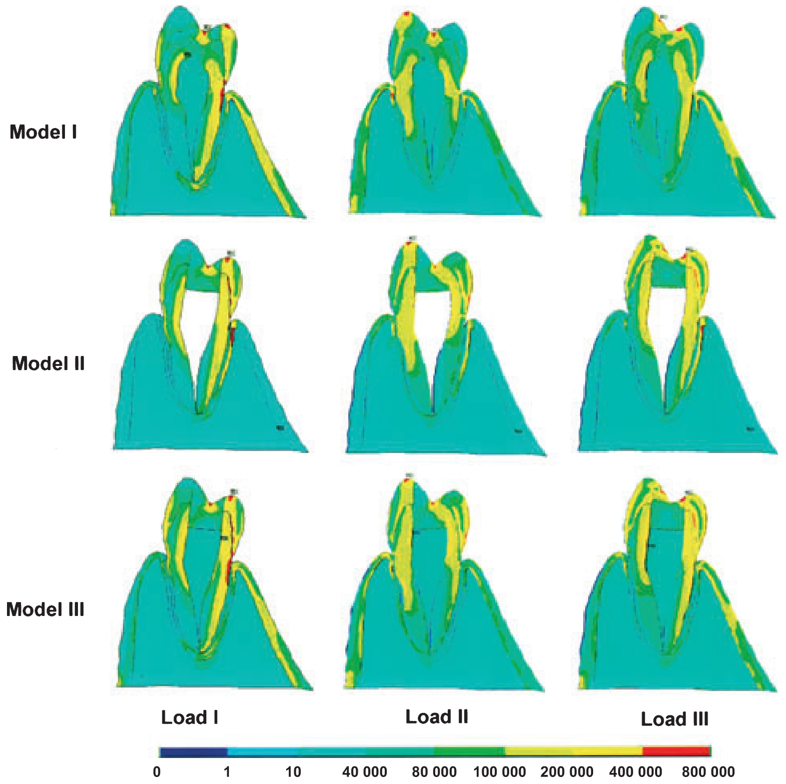

Figure 6 Equivalent stress distributions developed in the maxillary premolars at 2 ms after the teeth were subjected to various types of mastication forces. Models I, II, III represent the unprepared model, the cleaning and shaping treated model and the root canal filling treated model respectively.

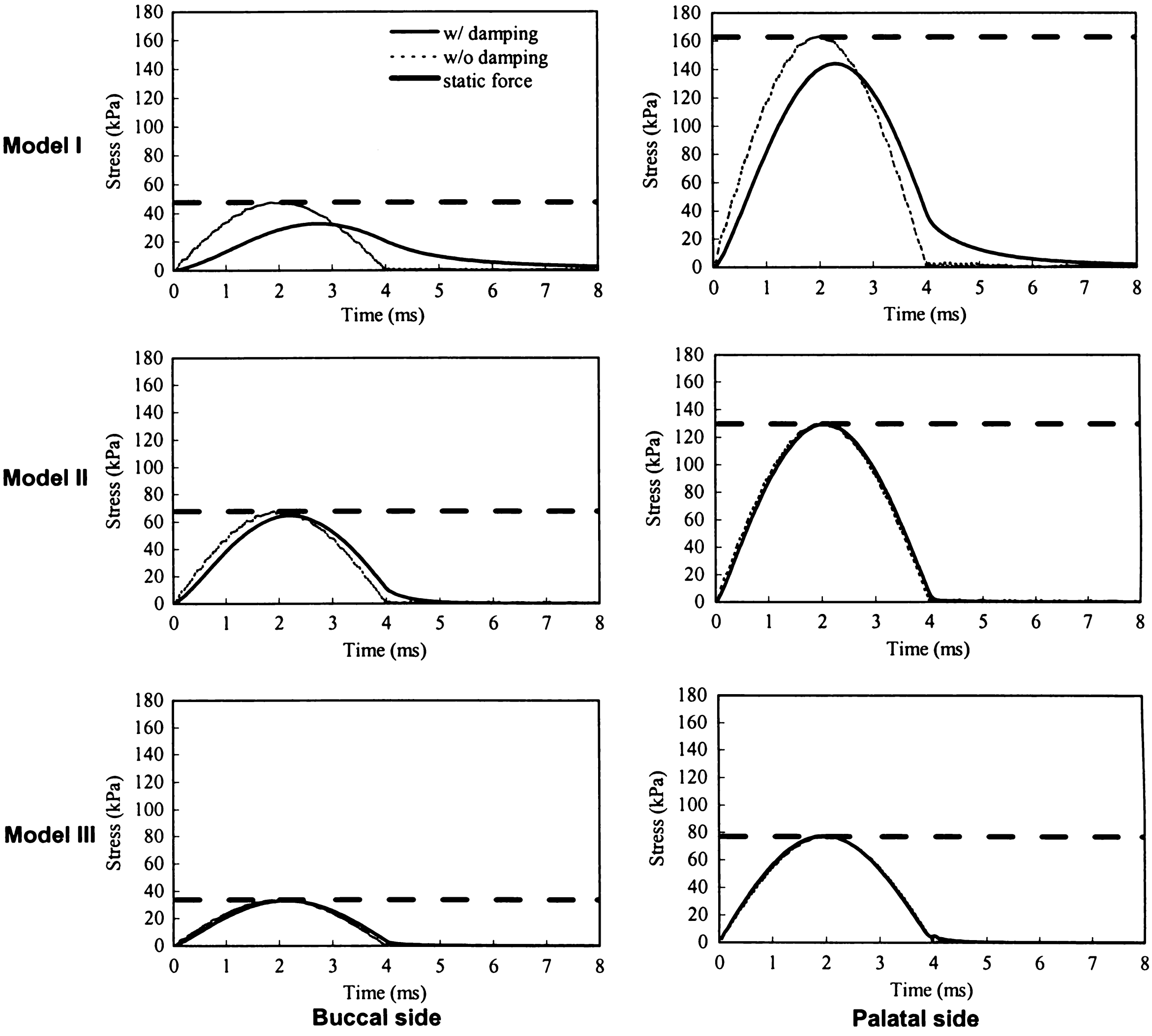

Figure 7 The equivalent stresses of static and dynamic analysis calculated over time in load I situation. The stresses were computed at the buccal and palatal sides of the roots. The dynamic analyses were performed with and without considering damping property.

buccal and palatal inclines (Fig. 9), a 13% reduction of stress could be seen on the buccal root (57.7 kPa and 50.0 kPa for undamping and damping models respectively). For all loading conditions, stresses calculated from static analysis were the same as the peak values obtained from dynamic analysis without considering damping properties in all three models.

Discussion

Previous clinical reports have indicated that maxillary premolars are the most common teeth to fracture after endodontic treatment (Tamse *et al.* 1999, Fuss *et al.* 2001). Therefore, we chose to use maxillary premolars as the research subject in this study.

Damping factor is a nonlinear property of a viscous material. It is defined as the fraction of strain energy lost in one full cycle of deformation (Oka *et al.* 1989). Therefore, a tooth with a higher damping ratio can dissipate more strain energy when it is subjected to a load. As shown in Figure 4, canal cleaning and shaping reduced the damping ratio value of the premolars. This is because the pulp and organic material in the dentinal tubule, the major organic components of the teeth that supply them with moisture, had been removed during treatment (Lee

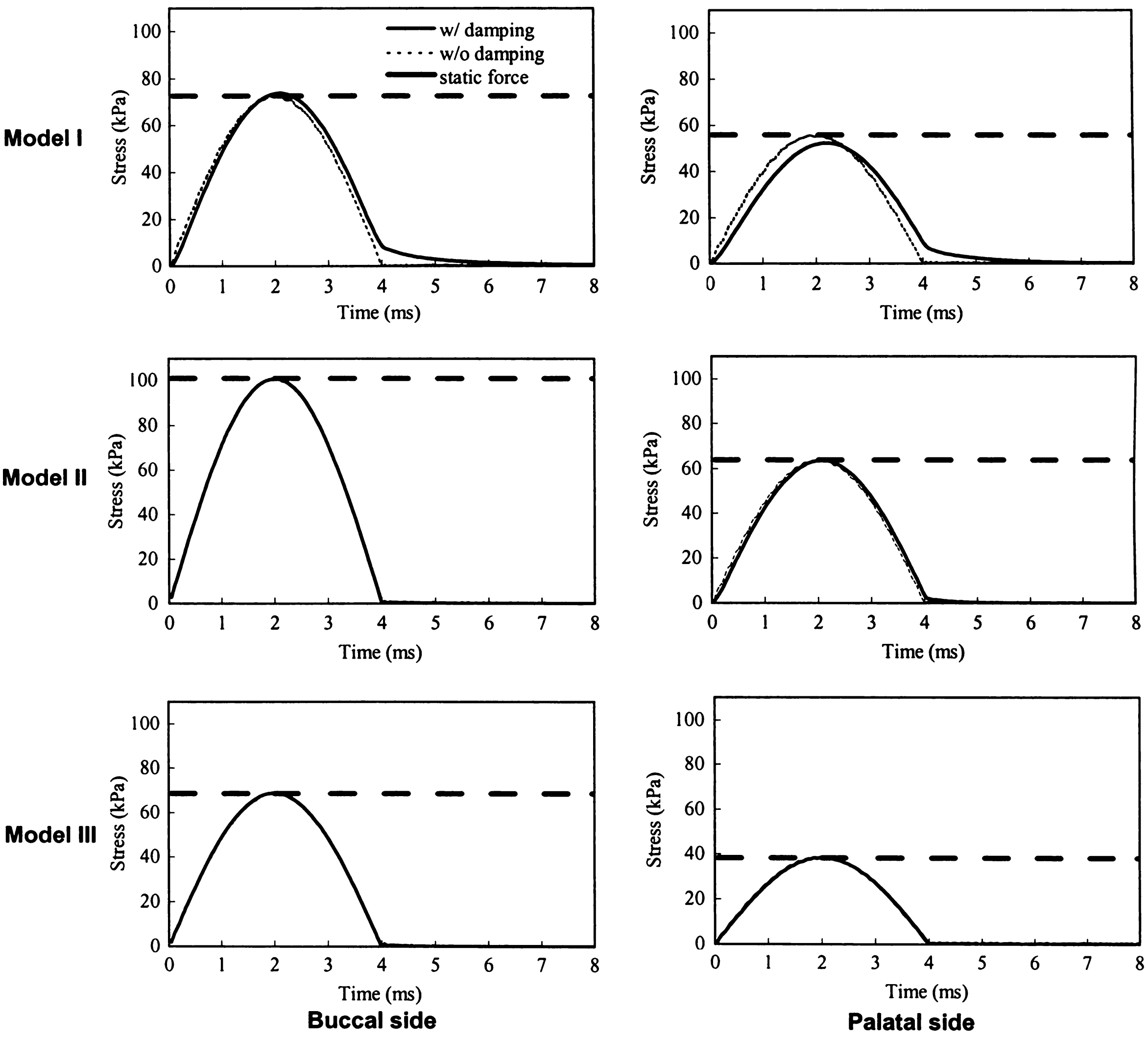

Figure 8 The equivalent stresses of static and dynamic analysis calculated over time in load II situation. The stresses were computed at the buccal and palatal sides of the roots. The dynamic analyses were performed with and without considering damping property.

et al. 2004). Although root obturation is helpful in increasing the damping ratio of root filled premolar, the ratio was still lower than that of vital unprepared teeth. This may explain why root filled demonstrate a higher risk of failure than teeth with vital pulp (Akkayan *et al.* 2002, Sathorn *et al.* 2005, Soares *et al.* 2008).

High stresses were concentrated at some specific areas, a result consistent with clinical findings (Fig. 6). These areas were around the points where the load had been applied, the root near the CEJ, and the area around the apical one-third. If one connects these areas of high stress, vertical crown-root fracture which has been reported to be the most common fracture mode of root filled teeth can be obtained (Chan *et al.* 1999).

As shown in Figure 5, the damping effects on stress reduction were observed only when the damping ratio was taken into account. The stress induced by static force was the same as the peak stress value in the premolar model without damping property. However, the stress is overestimated when compared with the results of the dynamic analysis that takes the viscous properties into account. Although previous studies have indicated that static analysis does not represent the clinical situation (Goto *et al.* 2005, Qing *et al.*

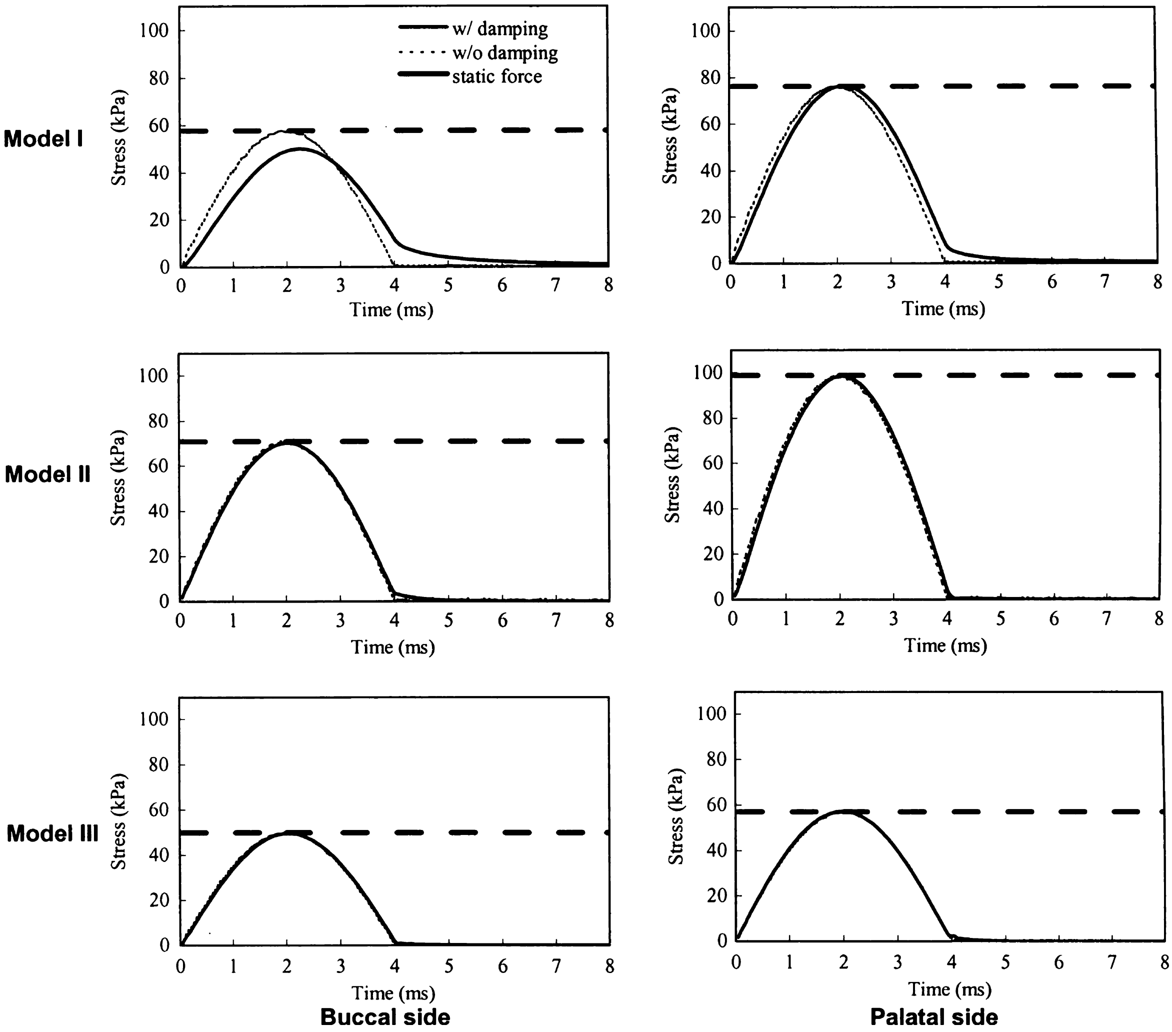

Figure 9 The equivalent stresses of static and dynamic analysis calculated over time in load III situation. The stresses were computed at the buccal and palatal sides of the roots. The dynamic analyses were performed with and without considering damping property.

2007), no previous study has estimated the error quantitatively. In this study, when the damping ratio was taken into consideration, peak stresses in the apical root of the unprepared premolars were 31.8% lower on the buccal side and 6% lower on the palatal side when loads were applied at palatal (Fig. 7) and buccal cusps (Fig. 8) respectively.

It has been well documented that external forces applied to teeth typically result from dynamic forces in real situations. In biomechanics, the damping properties of an impacted object cannot be ignored when a dynamic load is applied. This can explain the results of a previous study of static force (Huang *et al.* 1992) that demonstrated that loss of moisture has no effect on the fracture resistance of root filled teeth subjected to a static load. A previous study reported that intact teeth with healthy pulp have the highest degree of fracture resistance (Reeh *et al.* 1989). The stress analyses in the previous study also demonstrated that, regardless of whether damping property was considered, pulpless and endodontically treated premolars exhibited higher concentrated stress values at the area around the apical one-third of the root on the loading side, than for healthy intact teeth (Fig. 6). These results are probably due to the effects of changes in the size and geometric shape of the remaining dentine (Magne & Belser 2003, Soares *et al.* 2008).

The maximum stress developed in an unprepared intact premolar was greatly reduced by dispersing the strain energy over a longer period. This phenomenon is consistent with the findings reported previously (Huang *et al.* 2006). Clinical biologic materials, including periodontium and pulp, contribute to the attenuation of any impact stresses. However, the stress reduction effect was not found in those pulpless and root filled teeth. In the healthy intact premolar model, stress reduction effect was lower on the loaded than on the opposite side (Figs 7 and 8). Therefore, the strain propagation from the applied points to the opposite side must pass through pulp tissue, which can disperse the strain energy and hence reduce the concentrated stress. In this regard, it is reasonable to suggest that the pulp tissue contributes to the stress-reduction effect.

Dental treatment often involves removing tooth structure, which may alter the viscous property of the tooth, thereby resulting in a reduction of fracture resistance. Accordingly, softer liners in removable partial dentures (Wagner 1995), damper material made from artificial periodontal membranes (Mensor *et al.* 1998) and dental implants restored with a resin crown (Skalak 1985) have been introduced to increase the damping effects of treated teeth. In this study, obvious stress-damping effects can be seen only in the unprepared premolar, rather than the endodontically treated premolars. As the damping properties play an important role in the fracture resistance of endodontically treated teeth, it can be suggested that the damping properties should be taken into consideration when developing endodontic materials, such as intermediate restorative material, dental gutta-percha and composite resin, etc. in the future.

The limitation of this study is that the stress distributions in root dentine could not be observed three-dimensionally. However, two-dimensional models, which are more efficient at establishing models with various types of endodontic treatment, proved to be a useful in analysing the association between fracture resistance and stress distribution in teeth. In addition, stresses then occurred at the interface between the restorative material and the tooth were evaluated, as all the interfaces between different materials were assumed to be in perfect bonding. This could be a source of error that may need further investigation.

Conclusion

Pulp tissue of the maxillary premolars seems to play an important role in providing protective effects when teeth are subjected to an impact force. The damping ratio of human maxillary premolar measured in this study can be a useful reference in further related dynamic analysis.

Acknowledgements

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