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Influence of post fit and post length on fracture resistance

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Abstract

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Aim To investigate (i) the impact of post fit (form-congruence) and (ii) the influence of post length on the fracture resistance of severely damaged root filled extracted teeth.

Methodology Ninety-six single-rooted human teeth were root filled and divided into four groups (n = 24 per group). Post spaces were prepared with a depth of 6 mm (group 1, 3) and 3 mm (group 2, 4). Form-congruence with a maximal fit of the post within the root canal space was obtained in groups 1 and 2, whereas there was no form-congruence in groups 3 and 4. In all groups, glass fibre reinforced composite (FRC) posts were adhesively cemented and direct composite crown build-ups were fabricated without a ferrule. After thermo-mechanical loading (1200000×, 5–50 °C), static load was applied until failure. Loads-to-failure [in N] were compared amongst the groups.

Results Post fit did not have a significant influence on fracture resistance, irrespective of the post length. Both groups with post insertion depths of 6 mm resulted in significantly higher mean failure loads (group 1, 394 N; group 3, 408 N) than the groups with post space preparation of 3 mm (group 2, 275 N; group 4, 237 N).

Conclusions Within the limitations of this study, the fracture resistance of teeth restored with FRC posts and direct resin composite crowns without ferrules was not influenced by post fit within the root canal. These results imply that excessive post space preparation aimed at producing an optimal circumferential post fit is not required to improve fracture resistance of roots.

Keywords: endodontic post, form-congruence, fracture resistance, *in vitro* study, post space.

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Introduction

As root filled teeth often have insufficient coronal tooth structure, placement of a post is occasionally necessary to provide adequate retention for the core and final restoration. Alternatives to cast post-and-cores have been developed and include the use of pre-fabricated posts and custom-made cores with composite that facilitate a chair-side restorative procedure (Heydecke *et al.* 2002). In particular, fibre-reinforced composite (FRC) posts luted with adhesive materials have become more popular because of their favourable mechanical and aesthetic properties. For example, the elastic modulus of FRC posts is close to that of dentine, and results in the stress transmitted by a fibre post to the root dentine being lower than that caused by other materials such as titanium or zirconia (Duret *et al.* 1990). There is a controversy as to whether stress transmission and post rigidity has an impact on the fracture resistance and/or failure mode of root filled teeth with posts (Isidor *et al.* 1996, Akkayan & Gulmez 2002, Fokkinga *et al.* 2004). In addition to the presence of a post, other factors possibly influencing the load capability of root filled teeth are tooth morphology, restorative techniques and crucially the amount of tooth tissue lost (Trope *et al.* 1985, Gutmann 1992, Sornkul & Stannard 1992, Fernandes & Dessai 2001).

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When placing posts in accordance with standard clinical protocols, pilot drills are used to create a form-congruent root canal up to the apical third of the root to ensure primary post fit and retention. This optimized post fit can be termed 'form-congruence' (Schmage *et al.* 2005) and aims to create maximal adaptation of the post to the surrounding root canal walls with a thin and even post dentine cement interface. It is believed that form-congruence facilitates stress distribution along the canal wall during clinical function (Morgano 1996). Schmage *et al.* (2005) examined the form-congruence of five pre-fabricated titanium posts luted with zinc phosphate cement and found that the mean cement gap varied between 33 and 62 μm, depending on the post system. For root filled teeth with cast post-and-cores and crowns luted with zinc phosphate cement, a significant increase in fracture resistance was reported when a maximum adaptation of a tapered post to the residual root structure was present (Sorensen & Engelman 1990). This effect was not observed when parallel-sided posts were used. Preparing post spaces, however, poses several risks. The individual curvature and cross-section of the root canal may interfere with this preparation and create additional weakening of the root or even root perforation. Lang *et al.* (2006) investigated the impact of endodontic procedures on the deformation of anterior maxillary teeth and found that their stability decreases with every stage of the root canal preparation. A significant decrease in stability was observed when the post space was prepared, particularly following the transformation of the conical post preparations to a cylindrical form. It was concluded that if excessive amounts of tooth structure are removed and the natural geometry of the root canals are altered, this will have a destabilizing effect on root filled teeth. A recent study using computational, experimental and fractographic analyses has substantiated the impact of so called inner dentine located adjacent to the root canal on fracture resistance of teeth (Kishen *et al.* 2004). Obviously, it is not only the thickness of the dentine wall that stabilizes the root but also the presence of inner dentine with a lower elastic modulus than the more mineralized outer dentine. Particularly in irregular root canals with an oval cross-section, large diameter drills are required to ensure a circumferential post fit, and thereby excessive amounts of inner dentine are removed. Selecting a post that corresponds best to the natural root canal diameter without preparation, however, aims to preserve the inner dentine substance and may be associated with a loose-fitting post in irregular canals (no form-congruence).

As soon as posts are luted adhesively to the root canal walls, an ideal post fit within the canal (form-congruence) is probably less important as any spaces are filled with the luting composite. However, shrinkage of the thicker resin cement film by nonfitting posts may impair the clinical performance in the long term. Otherwise, even after standardized post space preparation (using the post hole drills supplied by the manufacturers) and optimal bonding procedures, the high-cavityconfiguration factor may lead to gap formation either along the cement-dentine interface or the cement-post interface (Pirani *et al.* 2005). To reduce the thickness of resin cement in irregular post spaces, Grandini *et al.* (2003, 2005) suggested a pre-cementation relining of the post with flowable composite (anatomical post) for the cementation of fibre posts to improve its fit to the canal space. In the light of this background, the use of adhesive techniques for post cementation and a minimal invasive post space preparation minimizing the loss of hard tissue are clinically preferable.

The aim of the present investigation was to study the influence of the form-congruence of adhesively luted glass FRC posts and of post length on the fracture resistance of root filled teeth. The null hypothesis was that (i) providing a form-congruence between post and post space preparation and/or (ii) reducing the post length would have no influence on the fracture load of root filled teeth restored with adhesively luted glass FRC posts and direct composite crowns.

Materials and methods

Ninety-six extracted single-rooted human teeth (maxillary lateral incisors and mandibular second premolars) were selected that fulfilled the following criteria: straight, sound roots, completely formed apices, absence of root caries and no visible fracture lines along the root. Teeth with similar dimensions at the cementoenamel junction (CEJ) in terms of root diameter and thickness of the dentine wall were distributed equally amongst the four groups. The teeth were stored in 0.1% thymol solution until further processing. The clinical crowns were removed 1 mm below the buccal CEJ using a diamond bur, leaving a root length of 13 ± 1 mm. All roots were cleaned with scalers.

Root canal preparation was performed using NiTi rotary instruments (Race, FKG, La Chaux-de-Fonds, Switzerland) under intermittent rinsing with 1%

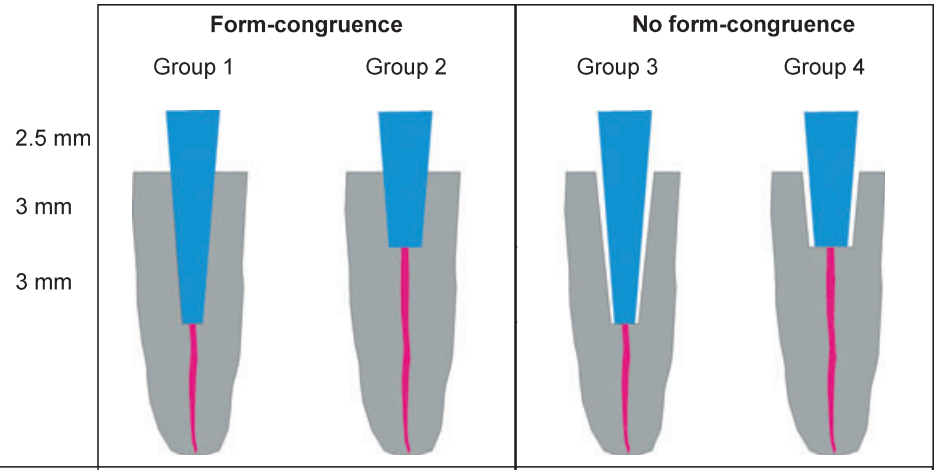
sodium hypochlorite to an apical size 45. The canals were then dried with paper points and filled with vertically compacted gutta-percha (Obtura II, Obtura Corp, Fenton, MO, USA) using an epoxy sealer (AH plus, Dentsply De Trey, Konstanz, Germany).

For each group, pre-fabricated glass FRC posts (FRC Postec, Ivoclar Vivadent, Schaan, Liechtenstein) with a 9.3% taper were used. Post spaces were prepared using appropriate drills with the same taper in a slow-speed contra-angle handpiece at 1000 rpm. For the 3 mm post length (group 2 and 4), the apical 3 mm of the post was cut off to obtain similar dimensions of the post diameter in the cervical region of all specimens (Fig. 1).

In groups 1 and 2, the size and shape of the bur corresponded to the FRC post to ensure optimal post fit (form congruence between post and post space). In groups 3 and 4, a more extensive post space preparation was created to simulate missing form-congruence between post and post space. For that reason, the pilot drill was shortened by 3 mm apically (group 2) and 6 mm (group 4). Because of the conical shape of the drill, the diameter of the post space preparation increases by about 300 μm along the whole length. This discrepancy between post space and post diameter results theoretically in a circumferential space width of 150 μm provided that the post is centered in the post space. The coronal part of the post was reduced in each group at the same level, i.e. 2.5 mm above the root canal orifice.

Restorative procedures

Prior to post cementation, the post space was rinsed with water for 30 s and dried with an air blow for 5 s and with paper points. Subsequently, all dentine surfaces were etched with one step (Ultra-etch, 35% phosphoric acid) for 15 s, rinsed with water spray for 15 s and dried carefully with an air stream for 5 s and with paper points, leaving the surface slightly moist. A dual-cure adhesive system (Excite DSC, Ivoclar Vivadent) was mixed and applied to the sample surface for 30 s. A gentle air stream was used to evaporate the dissolution fluid. The FRC posts were cleaned with alcohol and silanated (Monobond-S, Ivoclar Vivadent) for 60 s. A dual-curing resin luting material (Multicore Flow, Ivoclar Vivadent) was mixed and injected into the prepared root canal with an appropriate tip (C-R NeedleTubes, Centrix, Shelton, CT, USA). Subsequently, the post was seated using finger pressure for 10 s. Excess cement was spread with a brush in a thin layer



	Group 1	Group 2	Group 3	Group 4
Depth of post-space	6 mm	3 mm	6 mm	3 mm
Apical diameter of post-space	1 mm	1.3 mm	1.3 mm	1.6 mm
Apical post-diameter	1 mm	1.3 mm	1 mm	1.3 mm
Number of specimens analysed (*n*)	24	23	24	23

Figure 1 Schematic drawing of the post space preparation and the fibre reinforced composite post in the four groups.

so that it covered the occlusal surface of the specimens. The cement was light-cured (Optilux 500, Demetron/Kerr, Danbury, CT, USA) for 40 s in an occlusal direction.

To restore the coronal part of the teeth, direct composite crowns were built up with the same material (Multicore Flow). Despite slight differences in the cervical diameter of the roots, standardized crowns (4 mm height) were fabricated using transparent moulds (Pella crowns, Odus, Dietikon, Switzerland) with anatomically formed occlusal surfaces. Composite resin was placed free of bubbles in the mould, adapted to the tooth surface and then light-cured from each side for 40 s. Finally, the excess composite resin in the cervical area was removed and the margins of the restoration were finished using fine diamond burs. In each specimen, the tip of the post was covered with a layer of resin composite approximately 1.5 mm in height.

Mechanical loading

The roots of all specimens were coated with an air-thinned 0.3-mm layer of polyvinylsiloxane (President light body, Coltène-Whaledent AG, Altstätten, Switzerland) to simulate a periodontal ligament (PDL). The specimens were fixed with a light-curing composite on custom-made metallic holders (Provac, Balzers, Liechtenstein). The roots were then embedded in self-curing acrylic resin (Demotec 20, Demotec Siegfried Demel, Nidderau, Germany) so that the CEJ was situated approximately 1.5 mm above the simulated bone level (i.e. the upper margin of the embedding medium). After embedding, the samples were stored in water until loading.

All specimens were loaded mechanically at the centre of the occlusal surface using a computer-controlled masticator (CoCoM 2, PPK, Zurich, Switzerland). Stressing comprised 1.2 million occlusal loads of 49 N at 1.7 Hz obtained by using human cusps. Simultaneously, thermal stress was applied (3000 thermal cycles between 5/50 °C). These conditions are believed to simulate approximately 5 years of clinical service (Krejci *et al.* 1994).

After thermo-mechanical loading (TML), the fracture resistance was tested using a universal testing machine (Zwick, Ulm, Germany). Specimens were fixed in a metal holder with the long-axis of the roots at an angle of 45° to the load direction. A tin foil (0.5-mm thick) was placed between the steel sphere and the crown to avoid load peaks on the composite resin crown surface. The linear compressive load was applied (cross-head speed = 0.5 mm min^{-1}) at the central fissure of the occlusal surface in the direction of the buccal cusp until failure.

Statistical analysis

Primary outcome variable was failure during TML (fatigue testing). Second, loads-to-failure (in N) were compared when the specimens survived TML. Therefore, mean values and confidence intervals were calculated for the nonfailing specimens of each group. A significant difference between two groups is given when the confidence intervals do not overlap.

Results

Two specimens, one in group 2 and one in group 4, were lost because of failures in technical handling. All remaining teeth and restorations survived TML without loss of retention or visible fractures and were further tested for fracture resistance in the universal testing machine. Mean fracture loads after static loading are given in Table 1. There was no statistical significant difference between specimens with 6 mm post length without form-congruence (group 3) and group 1 (6 mm, form-congruence). Significantly, lower values were recorded for specimens with a 3-mm short post (groups 2 and 4). The lowest load values were

Table 1 Failure loads in the four groups

Group	*n*	Mean failure load (N)	SD (N)	95% Confidence interval for mean failure load (N)	
				Lower bound	Upper bound
1 (6 mm, form-congruence)	24	393.99^{A}	98.89	352.23	435.75
2 (3 mm, form-congruence)	23	275.47^{B}	75.61	242.77	308.16
3 (6 mm, no form-congruence)	24	408.06^{A}	130.20	353.08	463.04
4 (3 mm, no form-congruence)	23	236.74^{B}	96.27	195.11	278.37

Values exhibiting the same subscript number indicate no significant difference between the groups.

registered in group 4. In the current experimental set-up, form-congruence had no impact on fracture resistance, irrespective of the post insertion depth.

Discussion

The present study was conducted to evaluate the influence of form-congruence between post and post space as well as reduced post length in severely damaged root filled teeth. It was observed that post fit did not have a significant impact on fracture resistance, whilst short post length decreased load values significantly, meaning that they fractured more easily.

To gain information about the potential need for a maximum adaptation of the post to the canal wall, a lack of form-congruence was created in the current material by cementing a post in an over-enlarged root canal. The resulting gap was filled with flowable resin, which was concurrently used for the crown build-up to simplify the procedure. This is in accordance with a recent study suggesting that such materials lead to better retention than luting cement and therefore recommending them as alternatives for post cementation (Ohlmann *et al.* 2008). The results of the present study using resin cement clearly demonstrated that missing form congruence did not impair fracture loads. In contrast to these findings, Schmage *et al.* (2005) reported that only a post closely adapted to the root canal wall resulted in high retention and prevented stress peaks. They applied conventional luting material (zinc phosphate cement) and found that a thin homogeneous cement layer, where the film thickness was <50 μm, was essential to improve post retention. However, when the composite was used as a luting material, a mismatch between the diameter of the post space and that of the post did not impair retention (Assif & Bleicher 1986, Hagge *et al.* 2002), even when shrinkage of the thicker resin cement film resulted in more stress at the interface between the dentine and the post (Alster *et al.* 1997). Perez *et al.* (2006) investigated the impact of the resin cement thickness on the bond strength to the root canal dentine. Obviously, increased cement thickness did not reduce the bond strength significantly when FRC posts were inserted. These findings are in line with those of a recent study demonstrating that the accuracy of fit between post and root canal did not influence bond strength (Perdigao *et al.* 2007).

With the exception of the two technical failures, in the current experiment, all the teeth and restorations survived without loss of post retention or crown fracture. When loaded to failure, fracture loads in all groups were found to exceed the chewing forces normally associated with adults, which ranges from 7 to15 kg (Tortopidis *et al.* 1998). Teeth with 6-mm deep post preparations (groups 1 and 3) exhibited similar failure loads regardless of whether there was form-congruence between the post and the root canal. Specimens restored with 3 mm post length with or without form-congruence (groups 2 and 4) yielded significantly lower values. Again, the form-congruence of the FRC-posts had no influence on the load capability of root filled teeth. During the last decade, the use of resin composite for direct crowns in root filled teeth has been recommended only for temporary restorations. Laboratory investigations of the fracture resistance of resin composite crowns (with or without endodontic posts) have, however, yielded promising results, which suggest that their clinical application is appropriate (Krejci *et al.* 1994, Fokkinga *et al.* 2005). In a 5-year prospective clinical study on core restorations without crowns, Creugers *et al.* (2005a) demonstrated that only two out of 99 restorations failed. They found that direct composite build-up restorations exhibited high durability and a survival rate similar to that of crowned build-up restorations in the parallel trial (Creugers *et al.* 2005b).

To mimic a human periodontium (PDL), the roots of the tested teeth were covered with a layer of cured polyvinylsiloxane. The presence of this simulated PDL was found to significantly affect the results of fracture testing (Soares *et al.* 2005). The extracted human teeth used in the present study were sectioned 1 mm below the buccal CEJ, thereby removing the enamel completely. The remaining dentine surface is deemed to provide poorer bonding characteristics than enamel (Van Meerbeek *et al.* 2003). The prepared roots were provided with posts of different lengths and direct composite crown build-ups, but no ferrule was achieved. The advantage of a ferrule is that it generally facilitates a stabilizing effect by embracing the dentine. The tooth morphology established here, however, simulated that of a severely damaged root filled tooth. This situation is, according to the established clinical guidelines (Schwartz & Robbins 2004), ideally restored with a post and core build-up and a custom-made laboratory crown with circular ferrule (Stankiewicz & Wilson 2002). In most laboratory studies (Heydecke *et al.* 2002, Fokkinga *et al.* 2006, Salameh *et al.* 2007), this clinical recommendation is taken into account and the tested specimens revealed fracture loads higher than that in the current investigation. The ferrule

design of crowns is generally considered to be one of the most important factors to improve the load resistance of root filled teeth (Sorensen & Engelman 1990, Assif *et al.* 1993, Isidor *et al.* 1999, Akkayan 2004, Naumann *et al.* 2007). The present results reflect, therefore, the performance of the post and core alone, without being confounded by the additional value of a ferruled crown.

In the current material, TML was conducted to fatigue the samples prior to static loading. A repeatedly applied load in an aqueous environment simulates clinical conditions better than static loading alone. Using this environment, factors such as fatigue stresses or ageing, which influence the survival of materials can be taken into account (Naumann *et al.* 2005). However, the test designs of laboratory studies can only partially reflect the clinical situation. Clinically, loading is a dynamic process and loading forces, frequency and direction vary greatly. Because of the large number of other variables involved, including tooth condition, tooth type, applied restorative procedures and restorative materials used, it is almost impossible to compare the fracture resistance values obtained in different laboratory studies. In particular, the most unpredictable factor is the tooth conditions, which are mainly related to dentine (Kinney *et al.* 2003). This is an inherent drawback associated with the use of human teeth. It has been reported that testing human teeth results in a large standard deviation (Krejci *et al.* 2003), whilst artificially manufactured teeth are much more consistent (Ottl *et al.* 2002). In the present study, a sample size of 24 human teeth was chosen for each group to reduce the SD and to achieve more reliable results.

The findings of the present study strongly suggest that excessive post space preparation to maximize post fit and to reduce the amount of resin cement is not necessarily required. These results are particularly encouraging for teeth with oval or long oval root canal cross-sections. In such cases, not attempting to achieve a good circumferential post fit helps to preserve inner dentine and avoids additional weakening of the root. Further investigations should be conducted to study the effect of more oval pre-fabricated posts on the load capability.

Conclusions

Severely damaged root filled teeth restored with FRC posts and direct resin composite crowns without a ferrule revealed similar fracture resistance irrespective of the fit of the post, i.e. irrespective of form-congruence or no form-congruence. This suggests that post space preparation and a fitting post are not required to improve fracture resistance.

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References

Akkayan B (2004) An in vitro study evaluating the effect of ferrule length on fracture resistance of endodontically treated teeth restored with fiber-reinforced and zirconia dowel systems. *Journal of Prosthetic Dentistry* **92**, 155–62.

Akkayan B, Gulmez T (2002) Resistance to fracture of endodontically treated teeth restored with different post systems. *Journal of Prosthetic Dentistry* **87**, 431–7.

Alster D, Feilzer AJ, de Gee AJ, Davidson CL (1997) Polymerization contraction stress in thin resin composite layers as a function of layer thickness. *Dental Materials* **13**, 146–50.

Assif D, Bleicher S (1986) Retention of serrated endodontic posts with a composite luting agent: effect of cement thickness. *Journal of Prosthetic Dentistry* **56**, 689–91.

Assif D, Bitenski A, Pilo R, Oren E (1993) Effect of post design on resistance to fracture of endodontically treated teeth with complete crowns. *Journal of Prosthetic Dentistry* **69**, 36–40.

Creugers NH, Kreulen CM, Fokkinga WA, Mentink AG (2005a) A 5-year prospective clinical study on core restorations without covering crowns. *International Journal of Prosthodontics* **18**, 40–1.

Creugers NH, Mentink AG, Fokkinga WA, Kreulen CM (2005b) 5-year follow-up of a prospective clinical study on various types of core restorations. *International Journal of Prosthodontics* **18**, 34–9.

Duret B, Reynaud M, Duret F (1990) A new concept of coronoradicular reconstruction, the Composipost (2). *Le Chirurgien-Dentiste de France* **60**, 69–77.

Fernandes AS, Dessai GS (2001) Factors affecting the fracture resistance of post-core reconstructed teeth: a review. *International Journal of Prosthodontics* **14**, 355–63.

Fokkinga WA, Kreulen CM, Vallittu PK, Creugers NH (2004) A structured analysis of in vitro failure loads and failure modes of fiber, metal, and ceramic post-and-core systems. *International Journal of Prosthodontics* **17**, 476–82.

Fokkinga WA, Le Bell AM, Kreulen CM, Lassila LV, Vallittu PK, Creugers NH (2005) Ex vivo fracture resistance of direct resin composite complete crowns with and without posts on maxillary premolars. *International Endodontic Journal* **38**, 230–7.

Fokkinga WA, Kreulen CM, Le Bell-Ronnlof AM, Lassila LV, Vallittu PK, Creugers NH (2006) In vitro fracture behavior of

maxillary premolars with metal crowns and several post-and-core systems. *European Journal of Oral Sciences* **114**, 250–6.

Grandini S, Sapio S, Simonetti M (2003) Use of anatomic post and core for reconstructing an endodontically treated tooth: a case report. *Journal of Adhesive Dentistry* **5**, 243–7.

Grandini S, Goracci C, Monticelli F, Borracchini A, Ferrari M (2005) SEM evaluation of the cement layer thickness after luting two different posts. *Journal of Adhesive Dentistry* **7**, 235–40.

Gutmann JL (1992) The dentin-root complex: anatomic and biologic considerations in restoring endodontically treated teeth. *Journal of Prosthetic Dentistry* **67**, 458–67.

Hagge MS, Wong RD, Lindemuth JS (2002) Effect of dowel space preparation and composite cement thickness on retention of a prefabricated dowel. *Journal of Prosthodontics* **11**, 19–24.

Heydecke G, Butz F, Hussein A, Strub JR (2002) Fracture strength after dynamic loading of endodontically treated teeth restored with different post-and-core systems. *Journal of Prosthetic Dentistry* **87**, 438–45.

Isidor F, Odman P, Brondum K (1996) Intermittent loading of teeth restored using prefabricated carbon fiber posts. *International Journal of Prosthodontics* **9**, 131–6.

Isidor F, Brondum K, Ravnholt G (1999) The influence of post length and crown ferrule length on the resistance to cyclic loading of bovine teeth with prefabricated titanium posts. *International Journal of Prosthodontics* **12**, 78–82.

Kinney JH, Marshall SJ, Marshall GW (2003) The mechanical properties of human dentin: a critical review and re-evaluation of the dental literature. *Critical Reviews in Oral Biology and Medicine* **14**, 13–29.

Kishen A, Kumar GV, Chen NN (2004) Stress-strain response in human dentine: rethinking fracture predilection in postcore restored teeth. *Dental Traumatology* **20**, 90–100.

Krejci I, Mueller E, Lutz F (1994) Effects of thermocycling and occlusal force on adhesive composite crowns. *Journal of Dental Research* **73**, 1228–32.

Krejci I, Duc O, Dietschi D, de Campos E (2003) Marginal adaptation, retention and fracture resistance of adhesive composite restorations on devital teeth with and without posts. *Operative Dentistry* **28**, 127–35.

Lang H, Korkmaz Y, Schneider K, Raab WH (2006) Impact of endodontic treatments on the rigidity of the root. *Journal of Dental Research* **85**, 364–8.

Morgano SM (1996) Restoration of pulpless teeth: application of traditional principles in present and future contexts. *Journal of Prosthetic Dentistry* **75**, 375–80.

Naumann M, Sterzenbach G, Proschel P (2005) Evaluation of load testing of postendodontic restorations in vitro: linear compressive loading, gradual cycling loading and chewing simulation. *Journal of Biomedical Materials Research. Part B, Applied Biomaterials* **74**, 829–34.

Naumann M, Preuss A, Frankenberger R (2007) Reinforcement effect of adhesively luted fiber reinforced composite versus titanium posts. *Dental Materials* **23**, 138–44.

Ohlmann B, Fickenscher F, Dreyhaupt J, Rammelsberg P, Gabbert O, Schmitter M (2008) The effect of two luting agents, pretreatment of the post, and pretreatment of the canal dentin on the retention of fiber-reinforced composite posts. *Journal of Dentistry* **36**, 87–92.

Ottl P, Hahn L, Lauer H, Fay M (2002) Fracture characteristics of carbon fibre, ceramic and non-palladium endodontic post systems at monotonously increasing loads. *Journal of Oral Rehabilitation* **29**, 175–83.

Perdigao J, Gomes G, Augusto V (2007) The effect of dowel space on the bond strengths of fiber posts. *Journal of Prosthodontics* **16**, 154–64.

Perez BE, Barbosa SH, Melo RM *et al.* (2006) Does the thickness of the resin cement affect the bond strength of a fiber post to the root dentin? *International Journal of Prosthodontics* **19**, 606–9.

Pirani C, Chersoni S, Foschi F *et al.* (2005) Does hybridization of intraradicular dentin really improve fiber post retention in endodontically treated teeth? *Journal of Endodontics* **31**, 891–4.

Salameh Z, Sorrentino R, Ounsi HF *et al.* (2007) Effect of different all-ceramic crown system on fracture resistance and failure pattern of endodontically treated maxillary premolars restored with and without glass fiber posts. *Journal of Endodontics* **33**, 848–51.

Schmage P, Ozcan M, McMullan-Vogel C, Nergiz I (2005) The fit of tapered posts in root canals luted with zinc phosphate cement: a histological study. *Dental Materials* **21**, 787–93.

Schwartz RS, Robbins JW (2004) Post placement and restoration of endodontically treated teeth: a literature review. *Journal of Endodontics* **30**, 289–301.

Soares CJ, Pizi EC, Fonseca RB, Martins LR (2005) Influence of root embedment material and periodontal ligament simulation on fracture resistance tests. *Brazilian Oral Research* **19**, 11–6.

Sorensen JA, Engelman MJ (1990) Effect of post adaptation on fracture resistance of endodontically treated teeth. *Journal of Prosthetic Dentistry* **64**, 419–24.

Sornkul E, Stannard JG (1992) Strength of roots before and after endodontic treatment and restoration. *Journal of Endodontics* **18**, 440–3.

Stankiewicz NR, Wilson PR (2002) The ferrule effect: a literature review. *International Endodontic Journal* **35**, 575–81.

Tortopidis D, Lyons MF, Baxendale RH, Gilmour WH (1998) The variability of bite force measurement between sessions, in different positions within the dental arch. *Journal of Oral Rehabilitation* **25**, 681–6.

Trope M, Maltz DO, Tronstad L (1985) Resistance to fracture of restored endodontically treated teeth. *Endodontics and Dental Traumatology* **1**, 108–11.

Van Meerbeek B, De Munck J, Yoshida Yea (2003) Adhesion to enamel and dentin: current status and future challenges. *Operative Dentistry* **28**, 215–35.