International Endodontic Journal

doi:10.1111/j.1365-2591.2011.01851.x

The effect of the elastic modulus of endodontic posts on static load failure

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Abstract

Stewardson DA, Shortall AC, Marquis PM. The effect of the elastic modulus of endodontic posts on static load failure. *International Endodontic Journal.*

Aim To compare posts of different flexibility using static load testing. Hypotheses tested were (1) the flexural modulus of endodontic posts does not show a linear relationship with failure load and (2) the flexural modulus of endodontic posts does not show an association with failure mode.

Methodology Thirty 2 mm diameter rods of a glass fibre material Aesthetiplus (A), a carbon fibre Composipost (C) and stainless steel (S) were cemented into 90 roots of extracted human teeth using resin cement. Composite resin cores were added and the roots embedded in self-curing acrylic resin. Samples were loaded at 90° in a universal testing machine until failure. Failure loads and fracture levels were compared using one-way ANOVA and *post-hoc* Scheffé tests. Proportions of different failure modes were compared with Chi square tests ($\alpha = 0.05$).

Results Mean failure loads – MPa (SD) were A – 278.69 (85.79), C – 258.86 (82.05), S – 347.37 (74.50). There was no significant difference in the mean failure load of roots containing the FRC posts ($P = 0.639$), but it was significantly greater for steel post samples ($P < 0.01$). The mean level of fracture among the groups was not significantly different ($P = 0.879$). No root fractures were 'favourable'. Significantly more root fractures and fewer core fractures occurred for group A than for groups C or S ($P < 0.01$).

Conclusion The elastic modulus of an endodontic post does not appear to be a principal factor influencing load at failure or mode of failure of post-restored teeth.

Keywords: elastic modulus, endodontic post, fibre-reinforced composite, fracture, root, static loading.

Received 4 May 2010; accepted 21 December 2010

Introduction

Teeth restored with posts reportedly fail more frequently than other indirect restorations (Turner 1982, Mentink *et al.* 1993, Torbjörner & Fransson 2004), mainly through loosening of the post or less often by root fracture. For several decades posts have been made of metals; cast precious and non-precious metal alloys with an integral core and in more recent times, wrought prefabricated posts with a separate core of direct restorative material. Different metals and alloys exhibit a range of mechanical properties, but all have elastic moduli greater than the dentine of teeth (Kinney *et al.* 2003). It has been suggested that this mismatch in mechanical properties will give rise to unequal strain distribution and stress concentration in the dentine leading to root fracture (Dallari & Rovatti 1996, Qualtrough & Mannocci 2003) and this has been used to support the introduction of fibre-reinforced composite (FRC) posts. It is further suggested that when roots restored with FRC posts fracture, the level of fracture will be more coronal allowing re-restoration of the root – so called 'favourable fractures' (Sidoli *et al.* 1997, Mannocci *et al.* 1999). Others, however, consider that a rigid post is indicated to reduce root fracture (Manning *et al.* 1995, Asmussen *et al.* 2005).

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The relationship of the elastic modulus of the post to root fracture therefore warrants investigation so that evidence can be presented to clinicians to guide their clinical choices when providing post crown restorations. Static load testing has commonly been used in the assessment of post-restored teeth and there has already been a number of such studies comparing metal and FRC posts. These have provided conflicting results as to the influence of the flexural modulus of the post material on resistance to fracture. Some studies may be criticized for using posts of differing shapes and diameters (Sidoli *et al.* 1997, Stockton & Williams 1999, Raygot *et al.* 2001, Akkayan & Gulmez 2002, Mollersten *et al.* 2002, Al-Omiri & Al-Wahadni 2006). In others, information on the post dimensions was not reported (Dean *et al.* 1998, Maccari *et al.* 2003, Al-Omiri & Al-Wahadni 2006, Hayashi *et al.* 2006, Komada *et al.* 2006) which hampers the evaluation of the results and conclusions presented. Among studies in which fibre and metal posts of similar dimensions have been compared, it is reported that higher loads to failure occur with metal posts (Martinez-Insua *et al.* 1998, Newman *et al.* 2003, Naumann *et al.* 2005, Qing *et al.* 2007); with FRC posts (Barjau-Escribano *et al.* 2006) and that there is no significant difference in failure loads between metal or FRC containing roots (Ottl *et al.* 2002, Hu *et al.* 2003, Fokkinga *et al.* 2006).

Some have also assumed that all FRC posts have an elastic modulus close to that of dentine and that, among metal posts, their elastic properties may be considered to be equivalent without establishing the actual moduli of each of the materials or identifying trends in their results which correlate directly with the moduli of the materials. Most investigators have used sample sizes of 10, with some using smaller numbers. Their reported failure load values have coefficients of variation which range from just under 30% to over 50% (Mendoza *et al.* 1997, Martinez-Insua *et al.* 1998, Stockton & Williams 1999, Hu *et al.* 2003, Maccari *et al.* 2003, Al-Omiri & Al-Wahadni 2006, Qing *et al.* 2007) which considerably reduces the power of the statistical tests used to analyse their results. This is not acknowledged in studies, but the use of small sample sizes may help to explain the contradictory results which are reported and then used to support the use of either high or low modulus post materials. An alternative interpretation which has not been considered in explaining these conflicting findings is the possibility that the elastic modulus of the post is not of over-riding importance in determining resistance to fracture.

This study was undertaken to compare posts of different flexibility by means of static load testing with respect to the load at failure and to the mode of failure. The null hypotheses to be tested were 1, that the flexural modulus of endodontic posts does not show a linear relationship with failure load and 2, that the flexural modulus of endodontic posts does not show an association with failure mode.

Materials and method

To compare the effect of the modulus of the post on fracture of roots, representative post materials of the same diameter but with significantly different flexural moduli were obtained. These were 2 mm diameter rods of the carbon fibre material Composipost, the glass fibre composite Aesthetiplus (RTD, St. Egreve, France) and stainless steel, type T303 (Arenastock, Letchworth, UK). Three-point bend testing of 10 samples (span width 32 mm, sample length 48 mm) of these materials was carried out to confirm the flexural modulus of each of these materials according to ISO 3597-2:1993, Method 1008B:1996. An additional 30 samples of 20-mm length were then prepared to be used as endodontic posts.

Ethical approval was acquired and teeth were gathered from adult patients requiring tooth extraction at the Birmingham Dental Hospital, Birmingham, UK. Written consent to use the extracted teeth for experimentation was obtained from the patients. Extracted canine and maxillary incisor permanent teeth of similar root diameter were collected, i.e. the difference in maximum bucco-lingual diameter between the tooth roots was no greater than 1 mm. The incisors were randomly distributed into three groups followed by the canines so that there were equal numbers in each group. The teeth were stored in a 5% solution of Chloramine T (Fisher Scientific UK Ltd, Loughborough, UK) and used within 3 months of removal. Each tooth was examined using 3× magnification and transillumination. Any which contained cracks, defects or root caries were discarded. The teeth were sectioned perpendicular to their long axes at the enamel/cementum junction, the pulp tissue was removed and the canal space enlarged using endodontic hand instruments (K-files sizes 10, 15 and 20) and rotary Nickel Titanium files (rotary G.T. 0.6 taper, tip diameter 0.2 mm) (Dentsply Maillefer, Ballaigues, Switzerland). The canals were irrigated with a 3% solution of sodium hypochlorite (NaOCl) after each instrument. Post spaces were then prepared using a sequence of parallel-sided steel twist drills with water cooling (Axminster Power Tool Centre Ltd, Axminster, UK) to a diameter of 2.1 mm and a depth of 8 mm. A 17% aqueous solution of ethylene diamine tetraacetic acid (EDTA) was rubbed across the internal walls of the post space for 30 s using a microbrush (Microbrush Corp., Grafton, WI, USA) to remove the smear layer (REDTA, Roth Drug Co., Chicago, IL, USA) and flushed out with 5 mL of 3% NaOCl solution followed by 5 mL tap water. The space was carefully dried using absorbent paper points prior to placing a self-curing resin composite luting agent – Panavia 21 (Kuraray, Tokyo, Japan) Lot No. 41248. This product includes ED primer, a self-etching primer which was applied for 30 s and dried using a three-in-one dental air syringe for 20 s. Equal volumes of the base and catalyst of the cement were mixed and placed into the root using a spiral root filler in a dental handpiece. The posts were cleaned with 70% ethanol and allowed to dry for 10 min before being lightly coated with the mixed cement and fully seated into the post space. Excess cement was wiped away and the cement allowed to cure for 1 h. The protruding part of the post and the cut root face were then coated with a light-curing composite bonding agent, Excite (Ivoclar Vivadent, Schaan, Liechtenstein) Lot No. 25541 and cured using a hand-held dental curing light – Elipar 2500 (3M ESPE, St Paul, MN, USA) for 40 s.

A composite resin core Tetric Ceram, shade A1 (Ivoclar Vivadent, Schaan, Liechtenstein) Lot No. G05319 was then built up using transparent plastic caps from polymerase chain reaction (pcr) tubes (Omnistrips, Autogen Bioclear UK Ltd, Caine, UK) as moulds. A 2 mm diameter hole was placed at the centre of the top of the cap and after filling with composite, this was then pushed down over the post until it was firmly seated on the cut root face and centred around the post. Excess composite was carefully removed before curing from different directions for four periods of 60 s. The core was a truncated cone with a height of 4.5 mm, a base diameter of 4.6 mm and a top diameter of 4.5 mm. The original mesio-distal axis of the tooth was marked and the restored roots were then embedded to 1.5 mm from the top of the root in a self-curing acrylic resin, Total (Stratford-Cookson Co., Westbury, NY, USA) poured into 15 mm diameter polystyrene tubes. The post extending above the core was secured into the vertical arm of a dental laboratory surveyor (J.M. Ney Co., Bloomfield, CT, USA) so that the root could be maintained in a vertical position. Sample size and power for statistical testing by a one-way analysis of variance were calculated *a priori* using the freeware computer programme G*Power (version 3.1.2) Available at, http://www.psycho.uniduesseldorf.de/abteilungen/aap/gpower3/download-and-register. This indicated that, for an α of 0.05, a large effect size of 0.4 (Cohen 1969) and a power of 80%, a total sample size of 66 would be required. For a power of 90%, sample size would need to be 84. As the effect size was unknown, a slightly larger sample size of 90 was chosen. Thirty posts of each material were placed in a total of 90 roots and the embedded samples were stored with wet gauze in a sealed plastic box to maintain a moist environment.

Static load testing

After 1 week, each sample was fixed in an aluminium mounting block and subjected to compressive loading at 90° to the long axis of the teeth in an Instron 5544 universal loading machine (Instron Ltd, High Wycombe, UK). The load was applied at the midpoint of the core on the lingual/palatal side of the root at a crosshead speed of 0.1 mm min^{-1}. The first sharp drop in the load/displacement plot was recorded as the failure load.

Statistical analysis of all data was carried out using the statistical package SPSS v16 (SPSS Inc., Chicago, IL, USA). The data was first examined using Shapiro–Wilk and Levene's tests which confirmed a normal distribution and homogeneity of variance and the mean loads were then compared for statistically significant differences using one-way ANOVA with *post-hoc* Scheffé tests ($P = 0.05$).

Examination of failed samples

The mode of failure was determined by visual inspection and by microscopic examination of the surface of the root after the embedding acrylic had been carefully removed using a carborundum stone in a dental handpiece with water cooling. The vertical distance (mm) from the top of the root to the lowest extent of the fracture line on the surface was measured to determine the fracture level (Fig. 1). Comparison of the failure modes among the restored samples was performed with a Pearson Chi-squared test. Where a significant result was found, follow-up multiple comparisons were made with P values adjusted using the Bonferroni method to identify where the significant differences had occurred. Differences in the mean fracture levels of the roots containing each of the posts were analysed using one-way ANOVA with *post-hoc* Scheffé tests ($P = 0.05$). To

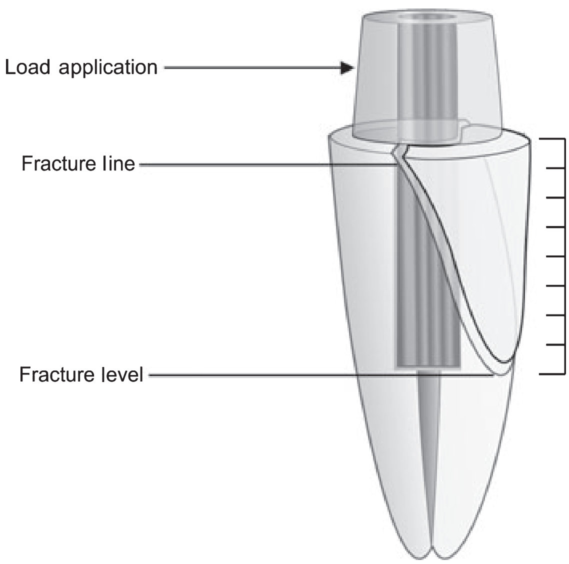

Figure 1 Diagram of post-restored root fractured during static load testing showing the determination of the fracture level.

characterize the failures among those samples where the mode of failure was not obvious, samples were cut perpendicular to the long axis of the root at 1 mm below the junction of the core and the root, from the mid-root area, and at 1 mm coronal to the apical end of the post. Basic fuchsin dye was applied for 10 s and then washed off with tap water to help the identification of interfacial gaps or cracks. The sections were viewed with an incident light microscope, Model M3C (Wild, Heerbrug, Switzerland) at up to ×80 magnification and digital photographs obtained (Nikon Coolpix 900; Nikon UK Ltd, Kingston-upon-Thames, UK). Samples with fractured cores were examined using a scanning electron microscope (SEM), JEOL 5300 (Jeol Ltd, Tokyo, Japan).

Results

Failure loads and failure modes

The mean flexural modulus and strengths of the three post materials as determined from three-point bending are shown in Table 1. There was no significant difference between the flexural strengths of either FRC post ($P = 0.687$), but these were almost twice that of the yield strength of the stainless steel post material. The flexural moduli of the materials were significantly different ($P < 0.001$) and encompassed a wide range of distinct values.

Table 1 Comparison of flexural properties of materials used in static load testing. Letters in columns indicate no significant differences between property values as determined by Scheffé post-hoc tests ($P < 0.05$).

Material	Flexural strength, MPa, mean (SD)	Flexural modulus, GPa, mean (SD)
Aesthetiplus	1398.87 (51.86) A	54.00 (0.71) C
Composipost	1437.12 (57.72) A	133.06 (1.05) B
Stainless steel (0.2% offset yield strength)	774.56 (138.53) B	189.16 (11.62) A

The failure loads recorded and the modes of failure determined by visual or microscopic examination are displayed in Table 2. There was no significant difference in the mean load to failure of the roots containing either of the FRC posts ($P < 0.639$), but the failure load was significantly greater for the roots with steel posts ($P < 0.001$ steel versus Composipost; $P = 0.006$ steel versus Aesthetiplus). Three separate modes of primary failure were observed:

1. *Fracture of the root*. In all cases, root fracture originated adjacent to the post at 90° to the direction of loading with the fracture line radiating obliquely downwards and forwards away from the point of load application towards the surface of the root.
2. *Debonding of the core*. Separation of the base of the core from the root surface without root fracture. Debonding of the core usually accompanied root fracture but in such situations this was determined to be secondary to root fracture.
3. *Core fracture*. Representative examples of static load samples are shown in Figs. 2 and 3. The embedding resin has been partially removed from samples which have failed during testing to show the fractured roots. Where root fracture was the mode of failure, the fracture line always extended below the level of the embedding resin. There were no 'favourable fractures'.

Examination of the roots in which fractures had occurred showed that for each post material, the fracture lines exited the root at different levels. There was no statistically significant difference in the mean level of fracture among the three groups ($P = 0.879$). Among the samples containing the lowest modulus post-Aesthetiplus, a greater number of root fractures and a smaller number of core fractures occurred compared with the other two materials. With the samples containing the highest modulus post material – steel, a greater number of failures resulted from fracture of the core. Significant differences in the

Table 2 Mean loads and modes of failure of teeth in static load testing. Letters in columns indicate no significant differences between values as determined by different statistical tests ($P < 0.05$).

Material	Failure load, Newtons mean (SD)	Co-efficient of variation	Failure mode: Root fracture	Core debond	Core fracture	Fracture level mm (SD)
Aesthetiplus	278.69 (85.79) A	0.32	14	13	3	4.58 (1.13) A
Composipost	258.86 (82.05) A	0.31	8	11	11	4.94 (1.47) A
Stainless Steel	347.37 (74.50) B	0.21	6	6	18	4.75 (1.92) A

proportion of the three failure modes were evident among the restored samples using a Pearson chi-squared test ($P = 0.002$). However, follow-up comparisons showed that the statistically significant differences between the post materials related to core fracture alone, with a significantly greater proportion of core fractures occurring among samples containing Composiposts than in Aesthetipost samples and also a significantly greater proportion of core fractures among the steel samples than in the Aesthetiplus samples.

SEM examination of fractured cores

Composite cores which had undergone fracture showed areas of plastic deformation where the loading roller had been placed, with a few crack lines radiating outwards. This appearance was seen on all fractured cores. Where parts of the core material had been lost it was possible to examine the interface of the post, bonding resin and core. Intimate adaptation of the bond resin to each of the post surfaces was evident but the steel posts showed large areas with no adherent remnants of bonding resin on their smooth surfaces indicating mainly adhesive failure at the bond resin/post interface (Fig. 4). The failure mode of the cores on the FRC posts was mixed with regions devoid of bond resin and core composite and other areas where thin layers of composite core were attached to the post's surface (Fig. 5).

Most of the cross-sections examined with the light microscope contained a continuous cement layer with very few voids between the root dentine and all of the post surfaces indicating uniform, even coating of the post and root walls. In some samples and at different levels, the variability of the internal anatomy of the pulp space was evident with the presence of fins extending into the dentine away from the post. Some of these had large voids where cement had not filled these spaces (Fig. 6).

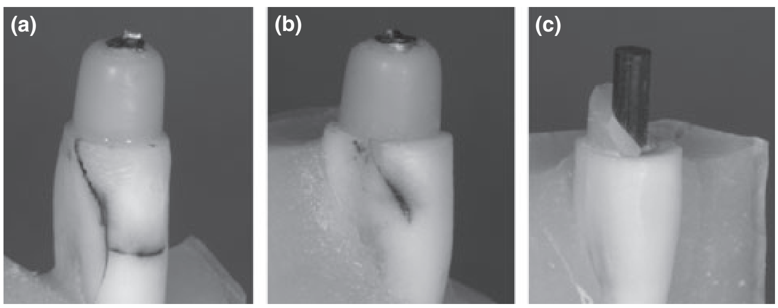

Figure 2 Representative failed static load samples containing steel posts (a, b) and carbon fibre post (c) with embedding resin partially removed. The fracture lines have been stained to help visualization. In c the core has fractured and separated from the carbon fibre post.

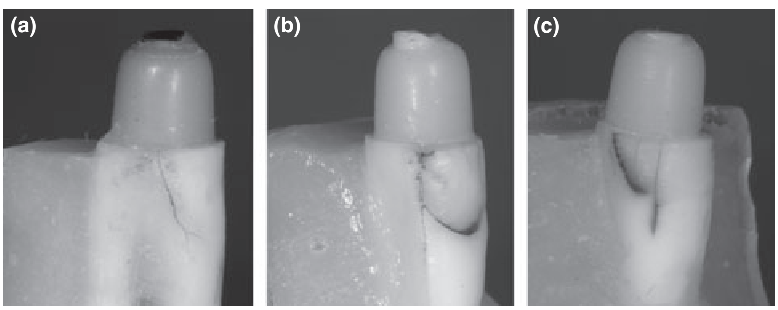

Figure 3 Failed static load samples containing carbon fibre (a) and glass fibre posts (b, c). The fracture lines seen in the samples containing each of the post materials show similar appearances.

Discussion

Static loading has frequently been used in the evaluation of post-restored teeth in an attempt to reproduce the pattern of loading which would occur clinically. It has the merit of being relatively simple and quick to carry out, but such studies may be criticized regarding their technical aspects and on the interpretation of test outcomes. The main criticism of static load testing is that it does not simulate the way loads are applied to teeth in the mouth and that the most frequent mode of failure in these tests, root fracture, differs from the predominant mode of failure observed clinically, i.e. decementation (Turner 1982, Mentink *et al.* 1993). Fatigue loading would appear to model more closely the natural intermittent pattern of loading. However, in many such studies, samples show no failure even after prolonged periods of intermittent loading (Mitchell & Orr 1998, Mannocci *et al.* 1999, Heydecke *et al.* 2002). As with static loading, where failure occurs, it is predominantly by root fracture (Isidor & Brondum 1992, Isidor *et al.* 1996, Goto *et al.* 2005, Sahafi *et al.* 2005, Jung *et al.* 2007) not through decementation and so fatigue testing may also be criticized as lacking clinical relevance (Kelly 1999). Within such an apparently simple test there is scope for the introduction of many variables. As teeth age, their physical and chemical structure changes (Ten Cate 1980), the dentinal tubules become occluded with dentine reducing the overall content of water (Toto *et al.* 1971). It has been shown that the fracture strength and fatigue resistance of teeth is less in old compared with young teeth (Arola & Reprogel 2005) and so may affect the results of load testing. As in most other studies, the age of the patients from whom the test teeth in this study were obtained was not recorded, but as all the teeth collected were maxillary anterior teeth with no or only small coronal restorations, it is likely that they were removed as a result of chronic periodontal disease and therefore that the majority of the patients would have been over 40 years of age providing some limitation in the age range of the teeth.

The method of use of the Panavia cement differed from that recommended by the manufacturer and was based on the following evidence. The preparation of post spaces is associated with the creation of a thick smear layer (Serafino *et al.* 2004) which impedes dentine bonding (Carvalho *et al.* 2004, Goracci *et al.* 2005). This is not readily removed by self-etch primers used for the manufacturer's recommended time (Ogata *et al.* 2002, El Zohairy *et al.* 2005) particularly mild

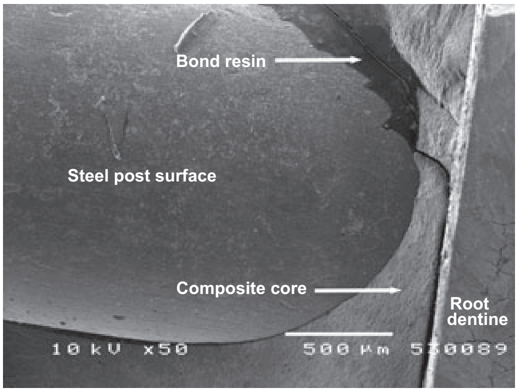

Figure 4 Low magnification of smooth steel post with partial loss of composite core. A gap can be seen at the bottom of the image between the remaining core and the post and there is separation between the core and the root surface (debonding).

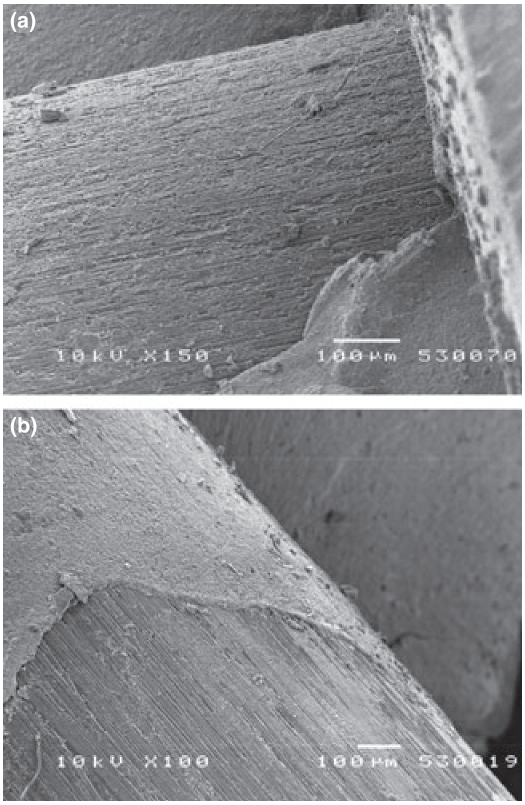

Figure 5 View of FRC post after core fracture showing: (a) Surface of a Composipost with only a few small fragments of core composite attached, and (b) Aesthetiplus sample with a broad layer of composite adhering to the post surface and an area where the core and bond resin have been lost.

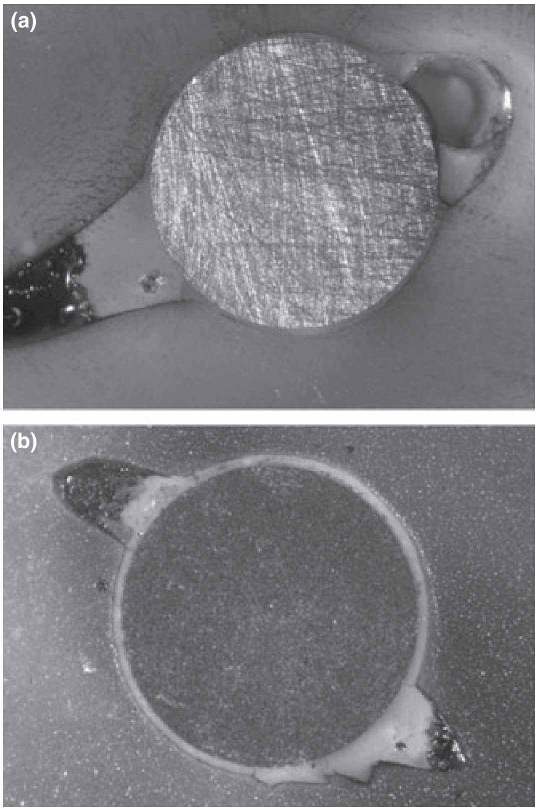

Figure 6 Light microscope images of cross-sections of post-restored teeth at (a) coronal and (b) midroot region of the tooth showing good adaptation of cement to the posts and elongation of root canal in the mesio-distal plane with incomplete filling of the pulp space by cement.

self-etch primers (such as the ED primer in Panavia which has a pH of 2.4–3). EDTA solutions have been shown to be particularly effective at removing smear layer and so pre-treatment with a 17% EDTA solution was used. Prolonged treatment may cause erosion of the dentine (Calt & Serper 2002) and therefore a 30 s duration was used. Similarly, having provided a smear-free dentine surface, the self-etch primer was applied for a reduced period of 30 s to avoid over-etching of the dentine which would remove all calcium from the collagen matrix to which the 10-MDP bonds chemically (Inoue *et al.* 2005). The manufacturer's recommendation that no cement should be placed into the post hole is intended to avoid premature setting of cement and failure to seat the post. This can happen because the setting reaction is accelerated when it comes into contact with the primer, and because of the warmth of the tooth in the mouth. *In vitro*, the tooth temperature is approximately 10 °C lower and it is easier to place the cement. Without coating the post space walls, cement will not be evenly distributed and will reduce post retention (Goldman *et al.* 1984, Reel *et al.* 1989). The use of a spiral filler has been shown to provide an even coating (Turner 1981). There were no incidences of failure to seat the posts in the test roots.

In this study, no root filling material was placed because in the subsequent preparation of a post space it may not be completely removed and so could have affected the cementation of the post (Bergeron *et al.* 2001, Hagge *et al.* 2002). Since variation in shape, length and diameter are known to influence stress distribution in posts (Davy *et al.* 1981, Cooney *et al.* 1986, Holmes *et al.* 1996), the dimensions of the different posts in this study were kept the same. In many static load studies, a load angle of approximately 135° has been employed as this represents the angle of occlusion of anterior teeth (Rock 1990). The load angle of 90° chosen for static loading in this work was not intended to reproduce a load angle which occurs *in vivo* but was selected to achieve a purely transverse load and a simpler initial comparison of differences in fracture resistance between samples containing different post materials. While it has been shown that the load required to cause fracture or failure increases as the loading angle increases (Eshelman & Sayegh 1983, Loney *et al.* 1995), in the study by Loney *et al.* (1995) the difference was not significant between angles of 110° and 130° and in neither study was a difference in the failure modes noticed. From the principles of mechanics, any force acting at an angle may be resolved into horizontal and vertical components. From the study by Loney *et al.* (1995), it may be seen that fracture resistance increases with increasing load angle (at least at angles greater than 130°), i.e. as the horizontal component is reduced. It is apparent therefore that the failure of post restored samples is as a result of the horizontal component of force. Loading at 90° applies only this relevant horizontal force; it also allows precise positioning of the loading nose avoiding any tendency for the loading nose to slide down the crown altering the point of application of load. The study by Loney *et al.* (1995) showed no significant difference in fracture resistance between 110° and 130° (the 'clinically relevant' load angle). As they did not apply load at 90°, it was therefore not demonstrated that a difference in fracture resistance occurred between 90° and 130°. Although some differences in fracture resistance were identified at different angles, they did not identify any significant difference in failure mode associated with different loading angles.

Therefore, while the load to failure will vary, testing may be undertaken at a convenient load angle without an apparent effect on failure mode.

The presence of a rigid crown is known to affect the stress distribution and fracture resistance of post-restored teeth (Assif *et al.* 1989, Toparli 2003) and that fracture resistance is significantly increased where a substantial ferrule can be created (Libman & Nicholls 1995, Ichim *et al.* 2006). In this study, static load samples were not fitted with crowns so that the influence of the elastic modulus of the post material could be established without being obscured by other factors (Patel & Gutteridge 1996, Reagan *et al.* 1999), but it is recognized that this does not simulate nor is it intended to simulate the clinical situation and that the results of these tests cannot be extrapolated directly to clinical behaviour. If crowns had been placed it would not have been possible to determine the relative contribution to fracture resistance of varying the elastic modulus of the post.

Although finite element analysis studies have suggested that the presence of a periodontal ligament (PDL) modifies the pattern of stress distribution (Davy *et al.* 1981, Rees 2001), coating the roots with a layer of silicone impression material in an attempt to simulate a PDL is at best optimistic: silicone impression material cannot reproduce the attachment to the root and bone which occurs *in vivo*, nor duplicate its viscoelastic nature. Furthermore, in static load experiments, its inclusion will be of little significance as it has been recognized that the elastomer quickly becomes compressed and is then unable to redistribute load (Good *et al.* 2008).

The post materials used in this evaluation provided a range of elastic moduli of approximately 3× (Aesthetiplus), 7× (Composipost) and 10× (steel) that of dentine (Peyton *et al.* 1952, Craig & Peyton 1958, Kinney *et al.* 2003). Consideration of the loads at which failure occurred showed that the roots restored with the highest modulus material failed at significantly higher loads than those which received the other two materials, but between the samples restored with the FRC posts no such difference was observed, despite the difference in their moduli. Therefore, there was no linear association between mean failure load and the modulus of these posts and the first null hypothesis is accepted. Although the elastic modulus values for the post materials determined using ISO standard dimensions were significantly different, no significant differences in failure loads were recorded. This may relate to the fact that the samples were post-restored roots in which the post lengths were clinically relevant and much shorter than required for the ISO standard and thus differences in mechanical properties may have less effect on failure.

The samples containing the different posts had different modes of failure. Root fracture, but also core debonding, was most frequent where the lowest modulus post Aesthetiplus had been used, while steel posts were associated mostly with fracture of the core. A more even distribution of failure modes occurred with the intermediate modulus post, Composipost. This could suggest that with the most rigid post, stress is widely distributed to the root and to the core/root interface. Because the post is rigid, the core composite is crushed between the post and the load applicator leading to its fracture. The larger proportion of core fractures on steel posts may also reflect an inferior bond between post and bond resin as suggested by the predominance of cohesive failure observed. As the modulus of the post material decreases, there is less resistance to bending of the core and of the root which increases the proportion of failure due to core debonding and root fracture. It is perhaps surprising that the loads at which failure occurred showed so little difference between the two FRC posts despite the large difference in their flexural moduli. While the trends in the failure modes appear linked to the posts' moduli, the statistical analysis of failure mode data supported this only with regard to core fracture and so the second null hypothesis cannot be rejected.

All of the root fractures observed extended well below the embedding acrylic which represents the alveolar bone. Therefore, if these had occurred clinically, none could be described as 'favourable fractures' as all would have resulted in removal of the tooth. De-bonding of the core from the root face would allow bacteria to access the dentine and initiate caries. This failure could be repaired by replacing the core and crown but only if it was recognized before significant carious damage had taken place. Fracture of the core would be unlikely to occur in the clinical situation if the core were enclosed by a metal crown. A ceramic crown may fracture, however, because the relatively low elastic modulus of the underlying composite core would not prevent flexure of the crown leading to tensile failure.

Examination of the root cross-sections showed that close adaptation of the luting cement to the root and post in the post space could be achieved with little evidence of voids or uneven coating at any level. However, the individual variation in the internal anatomy of the root canal means that in those samples where lateral extensions of the root canal space existed, additional surface area for dentine bonding was present. This may contribute to greater post retention, or the greater volume of resin cement could result in greater polymerization shrinkage stress leading to increased marginal gap formation and reduced bonding. If root filling had been carried out, these spaces may be blocked with filling material, which would also impact on the potential for bonding to the root dentine.

The design of this study attempted to reduce the number of variables present, but the post materials selected not only vary in their flexibility but also in their surface texture and chemical interaction with the cement used. The surface irregularity of the FRC posts should create more mechanical interlocking with the composite core than with the smooth steel posts. However, Panavia 21 cement used to lute the posts into the roots contains a bonding agent; 10 -methacryloyloxydecyldihydrogen phosphate (MDP) which forms chemical bonds with metal oxides such as those present in the passivation layer of stainless steel. These differences may be affecting the stress transfer at the post interface. The possible impact of the bond of the cement on static load failure should be investigated.

Conclusion

The elastic modulus of the endodontic posts did not show a linear correlation with mean failure load of post-restored teeth subjected to static load testing. This suggests that choosing a more flexible post will not by itself reduce the incidence of clinical failure.

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