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Failure analysis and survival rate of post and core restorations under cyclic loading

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Abstract

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Aim To investigate in a laboratory setting the influence of (i) post material (ii) preparation design and (iii) luting agent on the survival probability of root filled teeth, restored with all-ceramic restorations.

Methodology The crowns of 80 extracted single-rooted human teeth were removed, and root canal treatment was performed including canal filling with Gutta-percha without sealer (crown-down-pressureless technique). The root fillings were removed and the root canal enlarged with a reamer up to size 110. Prefabricated zirconia (CeraPost) or glass-fibre-reinforced posts (DentinPost) were luted using either Ketac Cem or Panavia F 2.0. A core build-up was applied (Clearfil Photocore), and the teeth were prepared with or without a 2-mm ferrule design ($n = 10$ per experimental group). The prepared teeth were scanned (Cerec 3D) and crowns fabricated. After luting of the crowns (Ketac Cem), teeth were subjected to thermocycling (×4000, 5–55 °C) and cyclic loading (1.5 million cycles, 90 N). After load cycling, the teeth were immersed in methyleneblue solution for 24 h and subsequently sectioned in three segments for a dye penetration test. Kaplan–Meyer analysis was performed to assess the survival probability followed by a Cox regression analysis ($\alpha = 5\%$).

Results Teeth prepared using the ferrule design as well as the teeth with DentinPosts exhibited a significantly higher survival probability ($P < 0.05$). The luting agent was of minor importance ($P > 0.05$). Most common failure was debonding of posts (CeraPost) and post fracture (DentinPost). The majority of the teeth showed dye penetration after cyclic loading.

Conclusions Post material and ferrule design were of paramount importance regarding the survival probability of the post and core restorations using prefabricated posts. DentinPosts showed superior results versus CeraPosts.

Keywords: all-ceramic crowns, cyclic loading, fibre posts, glass ionomer cement, resin-based luting agent, zirconium posts.

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Introduction

Restoration of root filled teeth prior to prosthodontic rehabilitation with fixed crowns or bridges often requires core build-ups. The build-up involves at least replacing of lost tooth structure using an alloplastic material to provide an adequate core for the preparation (Morgano *et al.* 2004). If the remaining tooth structure is inadequate for the stable retention of a direct core build-up material, a post must be placed into the canal to retain the core (Schwartz & Robbins 2004, Gu & Kern 2006).

Zirconia or glass-fibre-reinforced posts are available for chair-side procedures (Gu & Kern 2006, Naumann *et al.* 2006, 2009, Dietschi *et al.* 2007). The posts might be luted with conventional glass ionomer cements (GIC) (predominantly zirconia posts) as well

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as resin-based luting agents (zirconia and glass-fibre-reinforced posts) (Nothdurft & Pospiech 2006, Bitter & Kielbassa 2007, Nothdurft *et al.* 2008a,b).

The fracture resistance and survival probability (clinically intact restoration) of post and core restorations depend on several factors. These are the post material, the luting agent, the amount and condition of residual tooth structure, the core material, the preparation design and finally the fixed restoration (Stankiewicz & Wilson 2002, Peroz *et al.* 2005, Bitter *et al.* 2006c, 2007b, Kalkan *et al.* 2006, Dietschi *et al.* 2007, 2008, Naumann *et al.* 2009).

Laboratory studies, performed under realistic test-conditions, are important to assess the clinical suitability of these restorations and to identify potential reasons for failure (Dietschi *et al.* 2007, 2008). Studies mostly focus on one variable, e.g. luting agent or post system (Mannocci *et al.* 1999, Reid *et al.* 2003, Wrbas *et al.* 2007, Nothdurft *et al.* 2008a, 2009, Bitter *et al.* 2009b).

The aim of the current study was to evaluate the influence of three variables (post, luting agent and preparation design) on the survival probability of directly placed post and core restorations in a single protocol. This was the prerequisite to calculate the risk of failure using Cox regression analysis.

For artificial ageing, thermocycling was applied. Thermocycling reportedly influences the bond strength between the luting agent and root dentine (Bitter *et al.* 2006b, 2008). In addition, it is a major influencing factor regarding the degradation of the luting agent of all-ceramic crowns (Luthy *et al.* 2006). In contrast to other studies, teeth were not subjected to a static fracture test after load cycling (Mannocci *et al.* 1999, Rosentritt *et al.* 2000, Butz *et al.* 2001, Strub *et al.* 2001, Pontius & Hutter 2002, Reid *et al.* 2003, Sahafi *et al.* 2005, Hayashi *et al.* 2008, Nothdurft *et al.* 2008a). To identify occult disintegration and fatigue phenomena besides obvious failures under cyclic loading, a dye penetration test and SEM analysis were applied.

The null hypothesis tested was three-fold: The survival probability of directly fabricated post and core restorations covered with all-ceramic crowns is independent of (i) the post material, (ii) the preparation design and (iii) the luting agent used.

Material and methods

Preparation of the teeth

A total of 80 extracted human teeth with a single root canal (incisors, canines and premolars) with similar root architecture were pre-selected. The teeth were stored for no longer than 3 months in 0.1 wt. % aqueous thymol solution (Pharmacy of the University Hospital, Homburg, Germany). They were sectioned horizontally at the cemento-enamel junction to remove the clinical crown using a diamond-coated disc (WOCO 50; Uniprec, Clausthal-Zellerfeld, Germany) under constant water cooling. The cut surface was ground on wet SiC paper (grit size 4000) at 300 rpm (Gripo 2V; Metkon, Bursa, Turkey) to remove any remaining enamel (Naumann *et al.* 2009).

The dimensions of the root were determined and recorded using a digital calliper (NTD10-20C; Mitutoyo, Kawasaki, Japan). Only roots, meeting the following criteria, were included in the study: entire length >12.6 mm, bucco-palatal distance >4.1 mm at the root surface, mesiodistal distance at the root surface >3.8 mm, diameter of the root 3 mm from the apex >2.1 mm.

Root canal treatment was performed by enlarging and cleaning the canal using a crown-down pressure-less technique (1% NaOCl; Pharmacy of the University Hospital). For this purpose, Hedström files (VDW, Munich, Germany) of ascending sizes in subsequent order were used. The apical master file was size 40. Finally, the root canals were filled using Gutta-percha points (order no. 525; VDW) using a lateral compaction technique but no sealer. The teeth were kept wet during the entire preparation procedure. The filled roots were randomly assigned to one of two test groups for the placement of two different post systems, identical in shape but different in material (Table 1).

Then, the Gutta-percha root filling was removed up to a depth of 9 mm (±0.2 mm) using a pilot bur (order no. 183 LB; Brasseler, Lemgo, Germany), followed by root canal enlargement using a reamer (order no. 196; Brasseler, Lemgo, Germany) up to size 110. Finally, the inner surface of the root was roughened using a diamond-coated instrument (order no. 196 D; Brasseler), rinsed (70% ethanol; Pharmacy of the University Hospital) and dried.

The posts were luted using either GIC (Ketac Cem; 3M ESPE, Seefeld, Germany) or a resin luting agent (Panavia F 2.0; Kuraray, Tokyo, Japan). The GIC was dispensed directly from pre-dosed capsules onto the post prior to insertion into the root canal with slight rotating movements. Excess material was removed immediately.

For the adhesive luting procedure, a bonding agent (ED Primer II; Kuraray, Tokyo, Japan) was applied inside the root canal as well as onto the posts using

Table 1 Mechanical properties and composition of the posts used in the study compared with dentine

	CeraPost	DentinPost	Dentine[a]
Order no.	232L12–233L12	355TL12–356TL12	–
Composition	ZrO_2 ceramic (94.9% ZrO_2, 5.1% Y_2O_3)	Epoxy resin reinforced with silanized glass-fibres (60%)	–
Elastic modulus	200 GPa	30 GPa	15–30 GPa
Flexural strength	820 MPa	550 MPa	198–212 MPa

All data according to the manufacturers' information (Gebr. Brasseler, Lemgo, Germany).
[a]Intertubular Dentine – peritubular Dentine (Jameson *et al.* 1994, Kinney *et al.* 1996, 1999, Poolthong *et al.* 2001, Dietschi *et al.* 2007, Plotino *et al.* 2007).

microbrushes (Microbrush, Grafton, WI, USA). Excess material was removed using paper points (VDW). The pre-treated posts were coated with the resin luting agent (Panavia F 2.0; Kuraray) and placed inside the root canal with rotating movements. Excess material was removed with sponges, and the resin luting agent was light-cured for 60 s from all sides using a handheld light-curing unit (Astralis 7; Ivoclar Vivadent, Schaan, Liechtenstein).

Following this, the dentine and post surface were pre-treated using the corresponding bonding agent (Clearfil SE Bond; Kuraray) as recommended by the manufacturer. A core build-up material (Clearfil Photocore; Kuraray) was used in combination with preformed transparent matrices (Adapta Foil; Bego, Bremen, Germany) to construct standardized core build-ups. Clearfil Photocore was light-cured for 60 s.

The teeth were prepared with a shoulder preparation under copious water cooling using cylindrical diamond burs with rounded edges (order no. 837 KR and 8837 KR; Brasseler, Lemgo, Germany). Forty of the 80 teeth were randomly assigned to be prepared with the finish line located at the junction between core build-up and dentine. For the remaining 40 teeth, the finish line was located 2 mm apically of the junction between dentine and core build-up to obtain a so-called 'ferrule design'. Teeth were kept wet, when not being handled.

Fabrication and luting of the all-ceramic crowns

The prepared teeth were fixed in the socket of an acrylic model in the position of tooth 11 with adjacent teeth 21 and 12 (type AG-3; Frasaco, Tettnang, Germany) using silicone impression material (Optosil; Heraeus Kulzer, Hanau, Germany).

Teeth were optically scanned (Cerec 3D; Sirona, Bensheim, Germany). Single crowns were fabricated based on In-ceram alumina frames (thickness 0.7 mm), veneered with dentine mass (Vita VM7; Vita, Bad Saeckingen, Germany) with at least two dentine firings followed by a glass firing according to the manufacturer's instructions.

Final adjustment of the inner crown surfaces took place using diamond burs under constant water

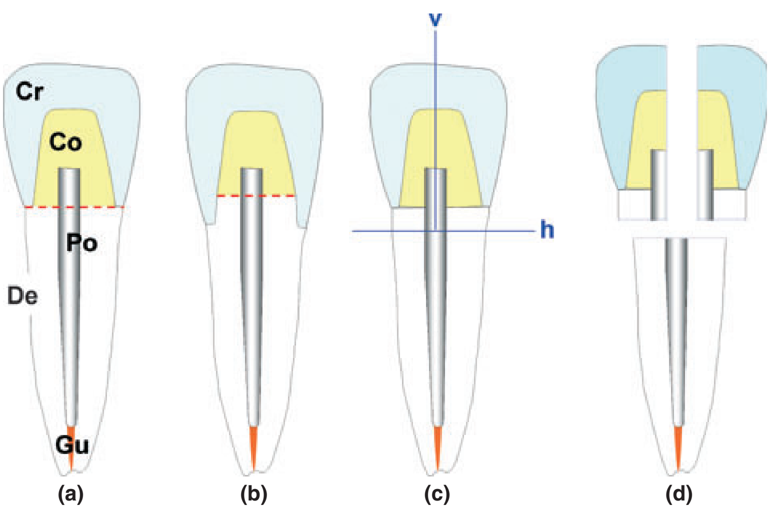

Figure 1 Schematic drawings of the tooth preparation. De, root dentine; Gu, Gutta-percha; Po, Post; Co, Core build-up; Cr, Crown. Red dotted line in (a) and (b): junction between core build-up and root dentine (a) preparation without ferrule design. (b) preparation with 2 mm ferrule design. (c) Direction of sectioning the teeth. h = horizontal section 2 mm below crown margin. v = vertical section in bucco-lingual direction. (d) Sectioned parts.

cooling. The inner surface of the crowns was sandblasted with 50-μm Al_2O_3 powder. All bonded surfaces (tooth as well as crown surfaces) were cleaned using ethanol prior to luting the crowns with GIC (Ketac Cem; 3M ESPE, Seefeld, Germany). All specimens were stored in deionised water (Pharmacy of the University Hospital, Homburg, Germany) after the luting procedure to prevent dehydration. Figure 1 shows a schematic drawing of the specimens obtained without (a) and with ferrule design (b).

Artificial ageing and cyclic loading

All specimens were subjected to thermocycling between 5 and 55 °C (dwell time 100 s) for 4000 cycles (Willytec thermocycler; SD Mechanotronic, Feldkirchen-Westerham, Germany). Following this, specimens were subjected to cyclic loading using a computer-controlled chewing simulator (Willytec dual-axis chewing simulator; SD Mechanotronic).

To simulate physiological periodontal conditions as recommended (Naumann *et al.* 2009), an individual tooth socket was prepared for each root in a PMMA block (Palapress Vario; Heraeus, Hanau, Germany). Polyether impression material was mixed according to the manufacturer's instructions (Impregum; 3M ESPE) and injected into the socket. The specimens were placed in the desired position within the socket and held in place using a jig, until the polyether impression material had set. The thickness of the simulated periodontal ligament was 350 μm (±50 μm).

Crowns of human premolars were fixed in the specimen holders of the computer-controlled chewing simulator to act as opposing teeth. The angulation of the longitudinal axis between teeth and specimens was adjusted to an angle of 135°, so that the antagonist contacted the crown directly above the palatal tuberculum.

Using a force of 90 N (speed of 40 mm s^{-1}, 1.8 Hz), 1.5 million chewing cycles were carried out. After each 250 000 cycle interval, specimens were visually inspected for damage (Table 2). Specimens, which were scored 1 and higher, were immediately removed from the chewing simulator and their score documented.

Table 2 Classification of failure events

Failure score	Description
0	No failure
1	Debonding of crown
2	Crown fracture
3	Debonding of post, including crown and core build-up
4	Post fracture at the level of the finish line
5	Post fracture within root canal
6	Root fracture

Evaluation and scoring

After 1.5 million chewing cycles, specimens were taken from the chewing simulator and removed from the artificial sockets. Following this, specimens were thoroughly inspected for damage under a light microscope (SMZ-140; Motic, Wetzlar, Germany) at 40× magnification.

Specimens, surviving the 1.5 million chewing cycles without any obvious defects (score 0 according to Table 2), were immersed in 0.5 wt. % methyleneblue dye solution for 24 h prior to re-inspection under the light microscope. Then, the teeth were sectioned vertically in bucco-palatal direction after the lower part of the root had been removed 2 mm below the crown margin (Fig. 1c,d). The cut surface of the segments was inspected for dye penetration according to the criteria displayed in Table 3. Representative pictures from sectioned specimens are given in Fig. 2.

All experiments were carried out at ambient laboratory conditions (23 ± 1 °C, 50 ± 10% r.h.). All materials were used according to their respective manufacturer's instructions.

SEM analysis

SEM analysis was performed to assess the transition area between posts and root dentine on representative

Table 3 Classification of dye penetration

	Dye penetration				
Score	Not detectable	Crown margin	Interface between core build-up and root	Entrance of root canal	2 mm inside root canal
0	X				
1		X			
2		X	X		
3		X	X	X	
4		X	X	X	X

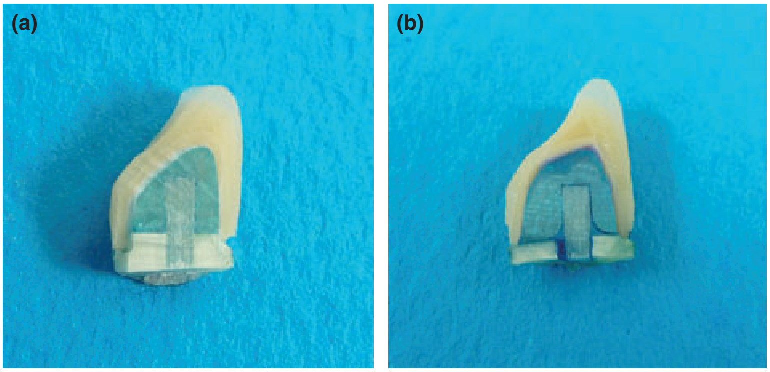

Figure 2 Representative pictures of the dye penetration test. Score 0 (a). Score 5 (b).

specimens. For this purpose, the coronal surface of the cut root was wet ground and polished on wet SiC paper grit 240–4000 (Buehler, Düsseldorf, Germany). Impressions were made from the surface and replicas cast using a two-component low viscosity epoxy resin (Stycast 1266; Emerson & Cuming, Westerlo, Belgium). Replicas were sputtered with Pt and subjected to SEM inspection in a scanning electron microscope (Quanta 200; FEI, Hillsboro, OR, USA) at ×125 to ×1000 magnification.

Statistical analysis

For the comparison of the root dimensions between the different test groups, parametric statistics were applied (Tukey's test), as data were normally distributed (Kolmogorov–Smirnov test, $P > 0.05$) and variances were homogenous (Levene test, $P > 0.05$).

As the number of chewing cycles in the chewing simulator represents defined clinical time intervals under masticatory forces, survival probability was calculated using Kaplan–Meyer analysis (Kaplan & Meyer 1958; Naumann *et al.* 2009, 2008). This procedure allows the assessment of the survival probability of an object over a given period. Kaplan–Meyer analysis requires definition of the survival event. This was defined as score 0 (no failure) according to Table 2.

A multivariate analysis (Cox regression analysis) was used to evaluate the influence of categorical covariates (i.e. post, luting agent and preparation design). The influence of the covariates was evaluated using the forward step-wise logistic regression method based on the likelihood ratio. All statistical analyses were carried out on a significance level of $\alpha = 5\%$ using the software SPSS (release 15.01; SPSS, Chicago, IL, USA).

Results

Table 4 depicts the results for the various root dimensions determined. There were no significant differences in root dimensions between the test groups (Tukey's test $P > 0.05$).

The failure frequencies occurring in the subgroups are listed in Table 5. In the CeraPost group, over 70% of the restorations failed within the 1.5 million chewing cycles, whereas <25% failed in the DentinPost group. Failures predominantly occurred in the nonferrule design groups. The most common failure in the CeraPost group was debonding of the post, followed by post or root fracture. Debonding preliminary occurred between the CeraPost and the luting agent. In contrast, the most common failure in the DentinPost group was post fracture.

Figures 3–5 shows the Kaplan–Meyer survival curves. Figure 3 denotes the survival probability of

Table 4 Root dimensions in the various test groups (mean values and standard deviations)

Experimental groups	Length (mm)	Mesiodistal (mm)	Bucco lingual (mm)	Apical diam. (mm)
CeraPost				
Ketac Cem	14.9 ± 1.6^a	5.5 ± 0.8^a	7.3 ± 0.8^a	2.9 ± 0.5^a
Panavia F 2.0	15.0 ± 1.6^a	5.3 ± 0.8^a	7.5 ± 0.9^a	2.9 ± 0.6^a
DentinPost				
Ketac Cem	15.0 ± 1.5^a	5.4 ± 0.7^a	7.2 ± 1.1^a	3.0 ± 0.4^a
Panavia F 2.0	15.8 ± 1.8^a	5.9 ± 1.2^a	7.0 ± 0.8^a	2.8 ± 0.4^a

Lowercase letters are related to columns, representing the results of the Tukey's test regarding root dimensions between the various test groups. Same letters denote results, which do not differ significantly ($P > 0.05$).

Table 5 Type of failure in the various experimental groups (in per cent accounted to 100% for each of the two post systems used)

Post	Luting agent	Design of tooth prep.	Type of failure: Debonding of crown (%)	Crown fracture (%)	Debonding of post[a] (%)	Post fracture at the level of the finish line (%)	Post fracture within root canal (%)	Root fracture (%)	No failure (%)
CeraPost n = 40 (= 100%)	Ketac Cem	Ferrule design	2.5	0	7.5	0	5	5	5
		Nonferrule design	0	0	10	2.5	10	2.5	0
	Panavia F 2.0	Ferrule design	2.5	0	0	0	0	2.5	20
		Nonferrule design	5	5	12.5	0	0	0	2.5
DentinPost n = 40 (= 100%)	Ketac Cem	Ferrule design	0	0	0	0	0	0	25
		Nonferrule design	0	0	2.5	2.5	0	2.5	17.5
	Panavia F 2.0	Ferrule design	2.5	0	0	0	0	2.5	20
		Nonferrule design	0	2.5	2.5	5	0	0	15

[a]Including Crown and core build-up.

CeraPosts vs. DentinPosts. The risk for failure was 5.9 times higher for CeraPosts compared with DentinPosts (Cox regression analysis $P < 0.001$; Table 6). In addition, the preparation design had a significant influence on the risk of failure (Cox regression analysis $P < 0.001$). However, the risk for failure without ferrule design was only 0.3 times higher compared with the group with ferrule design (Table 6, Fig. 4). In contrast, the influence of the luting agent on the risk of failure was insignificant (Cox regression analysis $P > 0.05$; Table 6). Nevertheless, there was a tendency for a lower survival probability for the GIC luted posts, as illustrated in Fig. 5.

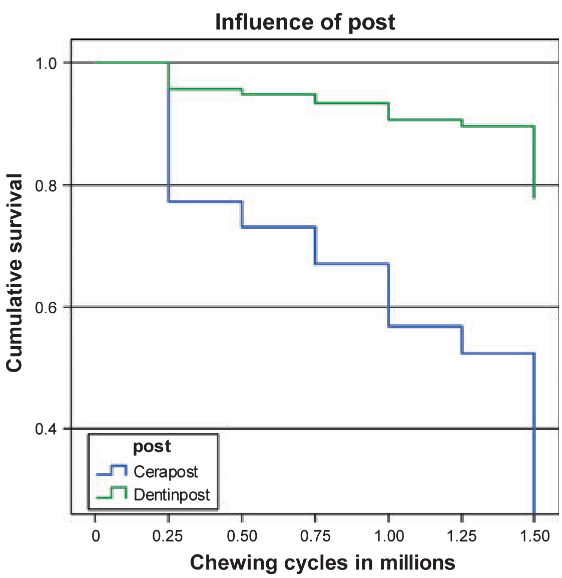

Figure 3 Kaplan–Meier survival curves, subclassified according to the post used.

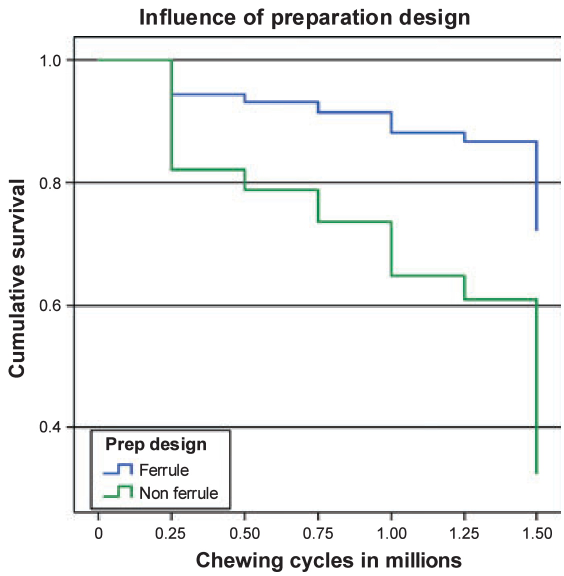

Figure 4 Kaplan–Meier survival curves, subclassified according to the preparation design applied.

Only 42 specimens (CeraPost: $n = 11$; DentinPost $n = 31$) survived the 1.5 million chewing cycles without obvious defects and were consequently subjected to the dye penetration test. In most cases, dye penetration occurred at least up to the interface between core build-up and root or deeper (Table 7).

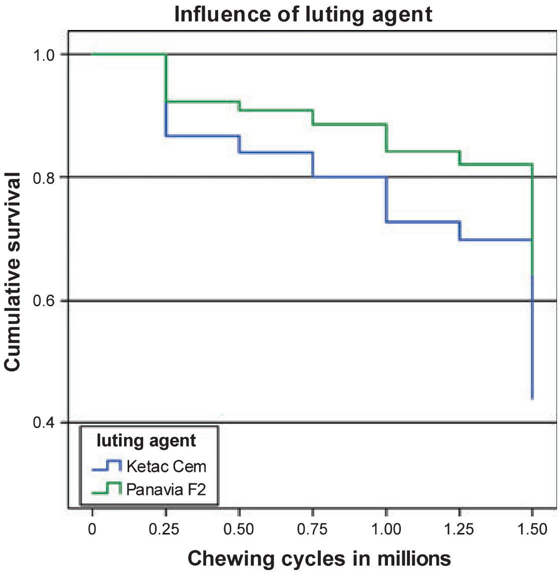

Figure 5 Kaplan–Meier survival curves, subclassified according to the luting agent used.

When luted with GIC, debonding primarily occurred between the DentinPost and luting agent. In some areas of the posts, a disintegration of fibres was visible in the periphery (Fig. 6a). The transition area of the resin luted DentinPosts showed debonding primarily between the cavity wall and resin luting agent, whereas the contact between the DentinPosts and Panavia F 2.0 was intact (Fig. 6b).

Also in the CeraPost group, debonding occurred primarily between the GIC and the post (Fig. 6c). In major areas of the roots inspected, a gap-free transition was noticed between the CeraPosts and the resin luting agent on the one hand, and resin luting agent and the root dentine on the other (Fig. 6d). However, whenever debonding was detectable, the gap occurred largely between luting agent and post.

Discussion

This study aimed at investigating the influence of post material, preparation design and luting agent on the survival of teeth restored with all-ceramic crowns. Summarizing the results requires rejecting the first and second part of the null hypothesis, as the survival probability was strongly dependent on the post material used as well as the preparation design. However, the third part of the null hypothesis could not be rejected.

The study design and testing parameters selected have proven their suitability in similar investigations (Rosentritt *et al.* 2000, Dietschi *et al.* 2007, 2008, Naumann *et al.* 2009). A simulated anterior tooth scenario was selected using all-ceramic crowns, as

Table 6 Result of the Cox regression analysis

Predictor variables	B	*P*-Value	Exp (B)	95% Confidence interval of Exp (B) Upper	Lower
CeraPost vs. DentinPost	1.768	<0.000	5.857	2.703	12.692
Panavia F 2.0 vs. Ketac Bond	0.607	0.070	1.834	0.951	3.537
Ferrule vs. Nonferrule design	−1.235	<0.001	0.291	0.145	0.584

B = Coefficient, Exp (B) = Hazard.

Table 7 Frequency of dye penetration scores (acc. to Table 3) for specimens, surviving the 1.5 million chewing cycles (CeraPost $n = 11$; DentinPost $n = 31$)

Post	Luting agent	Design of tooth prep.	Dye penetration score: Not detectable	Crown margin	Interface between core build-up and root	Entrance of root canal	2 mm inside root canal	No. of teeth surviving the 1.5 million chewing cycles
CeraPost	Ketac	Ferrule design	1	0	0	0	1	2
	Cem	Nonferrule design	0	0	0	0	0	0
	Panavia	Ferrule design	1	0	0	3	4	8
	F 2.0	Nonferrule design	1	0	0	0	0	1
DentinPost	Ketac	Ferrule design	4	0	4	0	2	10
	Cem	Nonferrule design	0	1	2	2	2	7
	Panavia	Ferrule design	3	0	0	2	3	8
	F 2.0	Nonferrule design	0	0	1	0	5	6

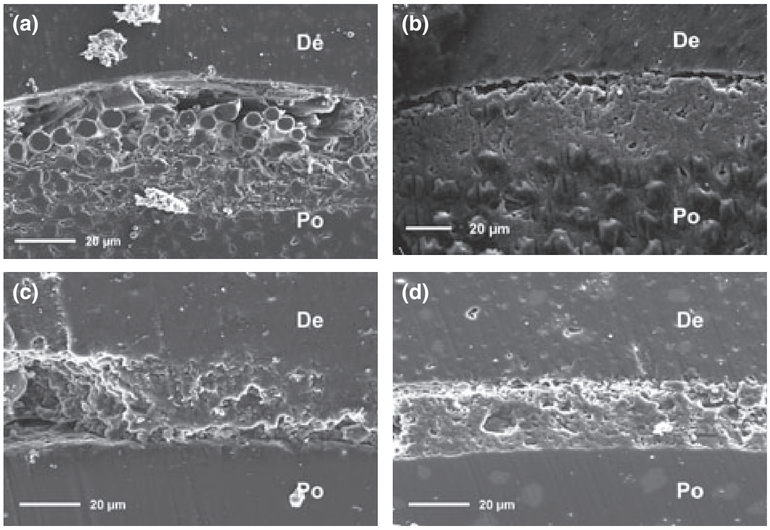

Figure 6 SEM micrographs of the transition area between post and dentine. De, root dentine; Po, post. (a) DentinPost luted with Ketac Cem. Note the disintegration of the outer fibres. A thin layer of Ketac Cem is attached to the root dentine. (b) DentinPost luted with Panavia F 2.0. Note the tight contact between post and luting agent, and gap formation towards the dentine wall. (c) CeraPost luted with Ketac Cem. Gap formation mainly between the post and luting agent. (d) CeraPost luted with Panavia F 2.0. Tight contact area.

anterior teeth are regarded a high risk area concerning mechanical failures because of a high amount of shear forces present (Torbjorner & Fransson 2004, Dietschi *et al.* 2008). The natural movement of teeth in the artificial sockets was simulated as described elsewhere (Rosentritt *et al.* 2000).

A cross-over design was selected, combining all post systems with all resin luting agents and preparation designs cross-wise to determine the best treatment option. Cox regression analysis demands this complete set of information to calculate the risk of failure, which was a central tool in the statistic analysis of the experimental data. Hence, the results obtained can clearly be ascribed to the variables tested. Another advantage was that both posts had an identical shape and did only differ in material.

Thermocycling reportedly leads to an alteration of luting agents and in turn might affect the internal stability of the root/luting agent/post complex (Bitter *et al.* 2008). It has to be considered, however, that the temperatures might not be identical under clinical conditions within the root canal *in vivo* (Walker *et al.* 2003, Bitter *et al.* 2006b). Nevertheless, thermocycling has a major impact on the bond strengths of the luting agent used to lute the crowns (Luthy *et al.* 2006). A root canal sealer was omitted on purpose to exclude its affect on the bonding ability to the root dentine as an influencing variable in the current experiment. This was regarded important, as some root canal sealer affect the bonding ability of resin-based luting agents (Menezes *et al.* 2008, Demiryurek *et al.* 2010).

Cyclic loading, in addition, leads to a flexion and deflexion of the root, even if minimal (Ferrari *et al.* 2008). This may affect the interfacial bonding between the luting agent and the post on one hand and luting agent and root dentine on the other. The 1.5 million chewing cycles applied are believed to simulate approximately 5–6 years in clinical service (Kern *et al.* 1999, Rosentritt *et al.* 2006).

In contrast to most of the studies identified (Mannocci *et al.* 1999, Rosentritt *et al.* 2000, Butz *et al.* 2001, Strub *et al.* 2001, Pontius & Hutter 2002, Reid *et al.* 2003, Sahafi *et al.* 2005, Hayashi *et al.* 2008, Nothdurft *et al.* 2008a), teeth were not subjected to fracture strength testing in the current experiment (Toksavul *et al.* 2005, Gu & Kern 2006). Thus, a direct comparison of the present results versus previously published data is limited because of significant differences in study design (Naumann *et al.* 2009).

A dye penetration test and SEM analysis were performed to identify possible weak points. The SEM analysis was carried out using a replica technique to reduce the risk of artefacts caused by the preparation procedure (i.e. dehydration) and shrinkage phenomena in the vacuum chamber of the scanning electron microscope. Another option for assessing the mode of failure would have been to use confocal laser scanning microscopy, which reportedly delivers more detailed results on hybrid layer thickness and mode of failure compared with a SEM analysis (Bitter *et al.* 2004, 2009a). However, information retrieved from the SEM analysis was sufficient to interpret the results obtained.

The results of the dye penetration test is regarded supportive information, as only 42 teeth survived the 1.5 million chewing cycles, reducing the number of specimens within the subgroups.

The results clearly indicate that the post material is of great relevance regarding the survival probability, which is in accordance with literature (Mannocci *et al.* 1999, Qualtrough & Mannocci 2003, Barjau-Escribano *et al.* 2006). This can readily be explained by the differences in elastic modulus between dentine and the post material (Table 1). Using CeraPosts might appear useful because of the high elastic modulus behind the rationale of reinforcing the tooth (Toksavul *et al.* 2005). However, this concept must be questioned due to the existing limitations in bonding the post to the root canal securely at both interfaces (Dietschi *et al.* 2007).

Debonding occurred primarily between Panavia F 2.0 and the CeraPost's surface, indicating a weak link. This hypothesis is corroborated by a recent study (Yun *et al.* 2010). In contrast, the bond strength between Panavia F 2.0 and root dentine is reportedly within a clinically acceptable range (Bitter *et al.* 2009b). CeraPosts, luted with GIC, showed disintegration phenomena primarily between the posts surface and the GIC. This is related to the observation that the bond strength between zirconia and a GIC is reportedly low (Gernhardt *et al.* 2005, Bitter *et al.* 2006c, Capa *et al.* 2009).

Besides bonding aspects, a high elastic modulus of the CeraPosts strongly limits flexion/deflexion of the post. Dentine, in contrast, will deflect in small areas under cyclic loading because of a higher flexibility (Ferrari *et al.* 2008). This inevitably leads to force peaks either at distinct areas/spots of the root – followed by root fracture – or to an enhanced internal tension at the interfaces leading to debonding, as observed (Joshi *et al.* 2001, Pegoretti *et al.* 2002).

In contrast, DentinPosts had a significantly higher survival probability. These results are believed to be related to the mechanical properties of the DentinPosts on one hand and their surface texture and composition on the other (Bitter & Kielbassa 2007a). Being in the range of natural dentine regarding elastic modulus (Kinney *et al.* 1996, 1999, Poolthong *et al.* 2001, Plotino *et al.* 2007), DentinPosts might follow closely the flexion and deflexion of the tooth/root, avoiding tension peaks (Joshi *et al.* 2001, Pegoretti *et al.* 2002). In consequence, using posts with similar physical properties as dentine seems appropriate (Gu & Kern 2006, Nakamura *et al.* 2006, Jung *et al.* 2007, Hayashi *et al.* 2008).

As denoted by the SEM micrographs, an intact and gap-free transition area was noticed between Panavia F 2.0 and the DentinPosts. These results are in accordance with literature (Bell *et al.* 2005, Bitter *et al.* 2006a, 2007b). It is hypothesized that the resin luting agent penetrates the posts surface building an interdiffusion zone and establishing a durable interface (Mannocci *et al.* 2005). On the other hand, a reliable bonding was achieved between the resin luting agent and the dentine surface (Bitter *et al.* 2004, 2006b, 2009b). When luted with Ketac Cem, gap formation was visible. These results are ascribed to the hypothesis that the GIC is less flexible than a resin luting agent on one hand, as well as a lack of interlocking and proper bonding to the posts' surface on the other (Bonfante *et al.* 2007).

The following interesting observation was made in the current study: At the interface between the GIC and the DentinPost, a disintegration of fibres was noticeable on the SEM micrographs, probably as the result of fatigue processes (Seefeld *et al.* 2007, Grandini *et al.* 2008). It is hypothesized that flexion and deflexion of a root under cyclic load lead to disintegration phenomena between matrix and fibres within the posts because of micromovements. This issue should be investigated in further studies. The post fracture, as the most common event in the DentinPost group, is most likely related to the lower flexural strength of the DentinPosts compared with zirconium posts, and/or a weakening of the DentinPosts, caused by the disintegration phenomena observed.

Besides the post material, the preparation design significantly affected the survival probability. The results unequivocally confirm that a ferrule design is mandatory to increase the fracture resistance of root filled–treated teeth (Assif *et al.* 1993, Naumann *et al.* 2006, Dietschi *et al.* 2007). Although not significant, posts luted with Panavia F 2.0 showed a tendency for a higher survival probability, which is in accordance with literature (Gu & Kern 2006).

Summarizing the results, it has to be pointed out that there are complex interactions between preparation design, luting agent and post material with regard to the survival probability of post and core restorations. The use of zirconia posts might become a treatment alternative to glass-fibre-reinforced posts, if a proper bonding between the zirconia surface and the luting agent can be achieved. Thus, further research should identify techniques and materials, respectively, to securely bond the luting agents to zirconia posts.

Conclusions

Under the limitations of this laboratory study, the following conclusion can be drawn: The ferrule design should be applied in daily practice whenever possible.

DentinPosts should be favoured over CeraPosts. Panavia F should primarily be combined with DentinPosts.

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