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Restoration of endodontically treated teeth with major hard tissue loss – bond strength of conventionally and adhesively luted fiber-reinforced composite posts

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Abstract – *Aim*: To evaluate the influence of the luting system on the pull-out bond strength of conventionally and adhesively luted fiber-reinforced composite posts (FRCPs). *Material and methods*: One hundred extracted bovine teeth (Di 3) were endodontically treated and randomly assigned to nine test groups and one control group (n = 10) according to luting system. After preparing the post cavities (8 mm), the custom-made FRCPs were inserted using conventional glass-ionomer cement (Ketac Cem), resin-reinforced glass-ionomer cement (Meron Plus and Fuji Plus), self-adhesive resin cement (RelyX Unicem and BisCem), self-conditioning adhesive and resin cement [Multilink Primer + Multilink and AdheSE + DC Activator + MultiCore Flow, or etch-and-rinse adhesive and resin cement (Seal-Bond Ultima + CoreCem, and LuxaBond + LuxaCore Z). As a control, custom-made titanium posts were inserted with Ketac Cem. After water storage (37°C, 24 h, dark), the pull-out test was performed, followed by failure mode evaluation. The data were statistically analyzed (α = 0.05) using analysis of variance and the Dunnett T3 *post hoc* test. *Results*: Luting system type and identity significantly influenced bond strength (P < 0.001); the bond strengths of all luting systems except Ketac Cem, MeronPlus, and BisCem were significantly higher than the control (4.4 ± 1.1 MPa). RelyX Unicem (12.0 ± 3.0 MPa) and LB + LCZ (14.8 ± 2.3 MPa) generated the highest bond strengths. The clinical application was demonstrated by restoring a traumatized tooth with extensive coronal destruction and thin root canal walls, using a FRCP combined with direct composite build-up. *Conclusion*: Luting system selection significantly influenced the bond strength of conventionally and adhesively luted FRCPs to bovine root canal dentin.

As a result of falls, fighting, sports, and bicycle accidents, approximately 18–25% of the human population suffers traumatic dental injuries during childhood and adolescence, usually before finishing school (1, 2). Maxillary incisors are most commonly affected, and crown fractures without pulp exposure are the predominant type of injury (58–73%) (3). For more severe injuries that result in pulp exposure, the treatment should aim to retain pulp vitality, especially in immature teeth, to ensure apexogenesis and thickening of the root canal walls by dentin apposition. In cases of pulp necrosis, endodontic treatment must be considered. The individual loss of tooth structure influences the treatment options in terms of restoration; endodontically treated anterior teeth with a minimal or moderate degree of destruction can be restored conservatively with bonded direct composite restorations. For severely destroyed teeth (<2 mm of tooth substance remaining), the use of posts is recommended to provide additional retention for the core build-up. Anterior teeth and premolars are more frequently treated with posts than are molars, due to the small retention area within the remaining dentin and enamel (4, 5).

The dental market offers a wide variety of post systems. Custom-cast gold posts or prefabricated metal posts (stainless steel, palladium alloy, titanium), luted with zinc phosphate or glass-ionomer cements, have been successfully used in the clinic for decades (6–9). However, the disadvantages of metallic post restorations include the unsatisfying esthetical outcome as well as the risk of vertical and horizontal root fractures. The distinctively higher modulus of elasticity of metal posts compared to dentin has been suggested to cause these fractures (10–12). Fiber-reinforced composite posts (FRCPs), with a modulus of elasticity similar to dentin, should solve this problem. FRCPs are believed to distribute stress more evenly through the tooth than metal posts, leaving the root less susceptible to fracture. The tooth-like color of FRCPs provides good esthetical properties (10, 11). Furthermore, FRCPs can be luted either conventionally or adhesively (5).

Conventional luting cements, such as glass-ionomer cements, are time-efficient, easy to use, less technique-sensitive, and inexpensive compared to adhesive luting systems (13). Conventional luting should therefore be suitable for both industrial and developing countries, where circumstances often narrow the treatment options. Although adhesive bonding of FRCPs is usually more complex, studies have reported higher bond strengths compared to conventionally cemented posts (14). For this reason, adhesive bonding was recommended as the method of choice for inserting FRCPs (15). By creating a monoblock between the post, the root, and the adhesive luting system, the remaining tooth substance can be stabilized (11). Considering the thin root canal walls of immature or young permanent teeth, this monoblock may reinforce the root and prevent fatal cervical tooth fractures (16–18). Nevertheless, the difficulty of adequate bonding within the apical third of the root canal (19), the occurrence of interfacial gaps along the hybrid layer surface, microleakage (20), and the high C-factor (21) challenge the efficiency of the adhesive technique for luting FRCPs.

Bond strengths can be increased by special pretreatments for posts, such as degreasing the post surface with alcohol/chloroform (22, 23), etching (24), sandblasting (24, 25), silicatization (26), and silanization (27). Pre-treating the post surface with an adhesive system may increase the bond strength by improving the wettability of the post surface.

Various methods are available for evaluating the bond strengths of luted posts; these methods are based on the principles of shear (push-out and pull-out test) or tensile force application (microtensile test) (28–30).

The purpose of this study was to evaluate the initial pull-out bond strengths of conventionally and adhesively luted FRCPs and to compare these strengths with the bond strength of conventionally luted titanium posts (TiPs). The first part of the study investigated the influence of post pretreatment (application of an adhesive system to the post surface) on bond strength between FRCPs and various adhesive luting systems. The null hypothesis was that the post pretreatment does not influence the bond strength. In the second part of the study, we evaluated the influence of the selection of the luting system on the bond strength of FRCPs that were conventionally and adhesively luted to bovine root canal dentin. The following null hypotheses were tested: (i) the luting system type does not influence the bond strength,; (ii) the selection of the specific luting system does not influence the bond strength, (iii) the bond strengths of conventionally and adhesively luted FRCPs do not differ from the bond strengths of conventionally luted TiPs and (iv) the bond strengths of the respective luting systems within one luting system type do not differ from each other.

Material and methods

Part 1: Influence of post pretreatment on bond strength between FRCPs and various adhesive luting systems

For this study, 160 samples consisting of a custom-made FRCP (smooth surface, size 6; RTD, St. Egrève, France) and the respective adhesive luting systems were prepared (Tables 1–3). All FRCPs were cleaned with 70% alcohol (FAU Pharmacy, Erlangen, Germany). The FRCPs of the groups MLP_ML, A_MCF, SBU_CC, and LB_LCZ [Multilink Primer (MLP), Multilink (ML), AdheSE (A), Multicore Flow (MCF), SealBond Ultima (SBU), CoreCem (CC), LuxaBond (LB), LuxaCore Z (LCZ)] (Table 1) were additionally pretreated with the respective adhesive systems, as recommended for dentin according to the respective manufacturer's instructions. After the post surfaces were pretreated, the posts were rolled in a reservoir of the respective resin cement. The posts were then axially inserted with a parallelometer (D-P26; Harnisch & Rieth, Winterbach, Germany) into an individually manufactured two-piece polytetrafluoroethylene mold (length 10 mm, diameter 6 mm) filled with the resin cement. All luting materials were cured accordingly to the manufacturer's instructions. The samples were then removed from the mold and individually stored in black microcentrifuge tubes (Carl Roth, Karlsruhe, Germany) in de-ionized water for 24 h (37°C). After preparing horizontal retention grooves, the samples were axially embedded with the parallelometer in acrylic resin (Technovit 4071; Heraeus Kulzer, Wehrheim, Germany) using molds (SampleKup; Buehler, Duesseldorf, Germany). The pull-out bond strength test was performed with a universal testing machine (Z2.5/TN1S; Zwick, Ulm, Germany; cross-head speed 5 mm per min); pull-out forces were measured in *N*. The bond strengths were calculated in MPa.

Part 2: Influence of luting system selection on the bond strengths of FRCPs conventionally or adhesively luted to bovine root canal dentin

Endodontic treatment

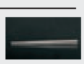
One hundred bovine deciduous front teeth (Mandibula Di 3) with straight root canals and fully developed apices were freshly extracted, cleaned of soft tissue and debris, and disinfected in 0.5% Chloramine-T solution for 1 week at 8°C. The crowns were removed at the cemento-enamel junction using a diamond disk (947D; Hager & Meisinger, Neuss, Germany), resulting in standardized root samples of length 17 mm.

The pulp tissue was removed with a barbed broach (VDW, Muenchen, Germany) followed by root canal cleaning and enlargement (working length 16 mm) using Hedstroem files and K-Files (ISO 15-80; VDW). During instrumentation, the root canals were intermittently irrigated with 1 ml of 5.25% sodium hypochlorite (Hedinger, Stuttgart, Germany) and 40% citric acid (FAU Pharmacy) between the instrumentation steps. After a final irrigation with 1 ml of 70% alcohol, the root canals were dried with paper points (ISO 80; VDW).

Table 1. Characteristics of luting systems used in the study

Luting system type		Luting system	Curing mode	Composition	LOT (Expiration date)
Conventional glass ionomer cement (CGIC)	KC	Ketac™ Cem Aplicap (3M ESPE, Seefeld, Germany)	Chemical	Glass powder, pigments, polyethylene polycarbonic acid, tartaric acid, water, conservation acid	376840 (2012-09)
Resin-reinforced glass ionomer cement (RRGIC)	MP	MeronPlus; (VOCO GmbH, Cuxhaven, Germany)	Chemical	UDMA, bis-GMA, HEMA, initiators, pigments, silica, polyacrylic acid solution	0932277 (2011-06)
	FP	Fuji Plus™ Conditioner	Chemical	Citric acid (10%), destilled water (87%), iron(III) chloride (3%)	0906241 (2011-06)
		Fuji Plus™ Capsule (GC Europe, Leuven, Belgium)		Alumino silicate glass, polyacrylic acid, hydroxyethyl-methacrylate, urethanedimethacrylate, water	0907221 (2011-07)
Self-adhesive resin cement (SARC)	RXU	RelyX™ Unicem Aplicap (3M ESPE, Seefeld, Germany)	Dual	Methacrylated phosphoric acid esters, triethyleneglycoldimehtacrylate, substituted dimethacrylate	375832 (2011-04)
	BC	BisCem® (Bisco Inc., Schaumburg, USA)	Dual	bis-GM A, uncured dimethacrylate monomer, glass filler, phosphate acidic monomer	0900010170 (2011-03)
Self-conditioning adhesive + resin cement (SCA + RC)	MLP_ML	Multilink® Primer A&B	Dual	Water, phosporic acid acrylate, HEMA, polyacrylic acid-modified methacrylate resin	M36892; M42208 (2011-12)
		Multilink® Automix (Ivoclar Vivadent, Schaan, Liechtenstein)		Dimethacrylate, HEMA, barium glass, ytterbium triflouride, spheroid mixed oxide	M41970 (2012-01)
	A_MCF	AdheSE® Primer	Dual	Dimethacrylate, phosphonic acid acrylate, water, initiators and stabilizer	M38939 (2011-10)
		AdheSE® Bond		Dimethacrylates, HEMA, silica, initiators and stabilizers	M44326 (2012-01)
		AdheSE® DC Activator		Ethanol, initiators	M12392 (2011-03)
		MultiCore® Flow Automix (light) (Ivoclar Vivadent, Schaan, Liechtenstein)		Bimethacrylates, inorganic fillers, ytterbiumtrifluoride, initiators, pigments, bis-GMA,TEG-DMA, UDMA, benzoylperoxide	M43997 (2012-01)
Etch and rinse adhesive + resin cement (ERA + RC)	SBU_CC	SealBond II Etching	Dual	Phosphoric acid (32%)	115910908 (2001-05)
		SealBond Ultima™		Acetone, biphenyldimethacrylate	0900005586 (2011-04)
		CoreCem™ (RTD, St. Egréve, France)		Bis-GMA, cilica, barium glass fillers, stabilizers, initiators	7906605 (2011-07)
	LB_LCZ	Etching Gel®	Dual	Phosphoric acid (37%)	626113 (2010-11)
		LuxaBond®		PreBond: ethanol arylsulfinate solution; Primer A: bis-GMA, catalyst; Primer B: bis-GMA, benzoyl peroxide	624741 (2010-11)
		LuxaCore® Z Dual (DMG, Hamburg, Germany)		Barium glass, pyrogenic silicid acid, nano fillers, zirconium oxide, bis-GMA	624696 (2011-06)

Table 2. Characteristics of the posts used in the study

Post type	Post	Composition	Surface roughness	Diameter	LOT	Picture
Titanium post (TiP)	Custom-made titanium post size 3 (NTI, Kahla, Germany)	Titanium	Rz 5.38, Ra 0.79	tip 1.1 mm end 2.2 mm	U10.001	
Fiber reinforced composite post (FRCP)	Custom-made fiber reinforced composite post size 6 (RTD, St. Egréve, France)	Quartz stretched fibers Epoxy resin	Rz 5.48, Ra 0.82	tip 1.3 mm end 2.2 mm	119390910	

The apical parts of all root canals were sectionally filled with 9 mm of gutta-percha (ISO 80; VDW) and sealer (AH plus; Dentsply De Trey, Konstanz, Germany). Excess sealer was removed using paper points. To allow the sealer to set and to simulate clinical conditions, the access cavities were first filled with Cavit-W (3M ESPE, Seefeld, Germany) followed by an adhesive sealing (Adper Prompt-L-Pop; 3M ESPE and Grandio Flow wo, VOCO, Cuxhaven, Germany). The specimens were stored for 1 day in de-ionized water at 37°C.

Table 3. Group classification after luting systems and post surface pretreatment for evaluating the influence of post pretreatment on bond strength between fiber-reinforced composite posts (FRCPs) and adhesive luting systems

Adhesive luting system	Group	Post pretreatment	Post	*n*
Multilink Primer (MLP)	ML	Alcohol	FRCP	20
Mulltilink (ML)	MLP_ML	Alcohol + adhesive system (MLP)	FRCP	20
AdheSe + DC Activator (A)	MCF	Alcohol	FRCP	20
MultiCore Flow (MCF)	A_MCF	Alcohol + adhesive system (A)	FRCP	20
Seal Bond Ultima (SBU)	CC	Alcohol	FRCP	20
CoreCem (CC)	SBU_CC	Alcohol + adhesive system (SBU)	FRCP	20
LuxaBond (LB)	LCZ	Alcohol	FRCP	20
LuxaCore Z (LCZ)	LB_LCZ	Alcohol + adhesive system (LB)	FRCP	20

Post insertion

The 100 samples were randomly assigned to nine test groups ($n = 10$) and one control group ($n = 10$). Table 4 shows the group classification according to the luting systems (Table 1) and posts (Table 2).

Before the post insertion procedure, the adhesive filling and 1 mm of the coronal part of the root were removed from all samples using a model trimmer with a diamond abrasive disk (HSSAZ; Wassermann, Hamburg, Germany). The post space was prepared to a depth of 8 mm (according to the post system) using pilot drills provided by the manufacturers (Ketac Cem, control group with titanium post (KC_co): RPR Titanium post finishing drill sizes 2 and 3, NTI, Kahla, Germany; all other test groups: Macro-Lock post finishing drill sizes 4 and 6, RTD). During the preparation procedure, the post cavities were intermittently irrigated with sterile de-ionized water. The root canals were rinsed and dried with paper points, and the roots were placed in silicon alveolar sockets to simulate the clinical situation during the post insertion and light-curing procedure.

Table 4. Group classification after luting system types, luting systems and post types for evaluating the influence of luting system selection on bond strength of conventionally or adhesively luted fiber-reinforced composite posts (FRCPs) to bovine root canal dentin

Luting system type	Group	Luting system	Post	*n*
Conventional glass ionomer cement (CGIC)	KC_co	Ketac Cem (KC)	TiP	10
	KC	Ketac Cem (KC)	FRCP	10
Resin-reinforced glass ionomer cement (RRGIC)	MP	Meron Plus (MP)	FRCP	10
	FP	Fuji Plus (FP)	FRCP	10
Self-adhesive resin cement (SARC)	RXU	RelyX Unicem (RXU)	FRCP	10
	BC	BisCem (BC)	FRCP	10
Self-conditioning adhesive + resin cement (SCA + RC)	MLP_ML	Multi Link Primer (MLP) Mullti Link (ML)	FRCP	10
	A_MCF	Adhese (A) Multi Core (MC)	FRCP	10
Etch and rinse adhesive + resin cement (ERA + RC)	SBU_CC	SealBondEtching (SBE) Seal Bond Ultima (SBU) CoreCem (CC)	FRCP	10
	LB_LCZ	Etching Gel (EG) Luxa Bond (LB) Luxa Core Z (LCZ)	FRCP	10

The luting systems were used following the manufacturers' instructions. All posts [FRCP: size 6, RTD (surface roughness Rz 5.48, Ra 0.82); TiP: size 3, NTI (surface roughness Rz 5.38, Ra 0.79)] were cleaned with 70% alcohol. For the groups consisting of a dentin adhesive system (MLP_ML, A_MCF, SBU_CC, LB_LCZ), the posts and the post cavities were pretreated with the respective adhesive systems.

The luting cements were applied to the posts by rolling them in a luting material reservoir on a mixing pad and by applying the cements directly into the post cavity [KC_co, KC, MeronPlus (MP), and Fuji Plus (FP): Needle Tubes, Centrix, Shelton, USA; RXU: RelyX Unicem Aplicap Elongation Tips, 3M ESPE; BC, MLP_ML, A_MCF, SBU_CC, and LB_LCZ: Endotips, RTD]. The posts were then inserted into the post cavity, ensuring that the protruding part of all posts had the same length as measured from the canal orifice. The excess luting material was gently removed, avoiding material deficit in the gap between post and root canal wall; a 0.5-mm polyethylene foil followed by a 2.0-mm polyethylene foil (Erkodur; Erkodent, Pfalzgrafenweiler, Germany) with central holes was placed over the post and pressed onto the coronal sample surface to remove the remaining excess luting material. The luting materials were cured according to the manufacturers' instructions. The specimens were individually stored in black microcentrifuge tubes in deionized water at 37°C in the dark for 24 h.

Bond strength testing procedure

Before embedding the samples, three horizontal retention grooves were prepared on the root surface using a steel bur (1RF012; Hager & Meisinger). After the specimens were axially lined up with the molds (SampleKup) by placing the posts in a parallelometer with a three-jaw drill chuck (D-P26), the samples were embedded in acrylic resin (Technovit 4071; Heraeus Kulzer).

The embedded specimens were subjected to the pull-out test in a universal testing machine (Z2.5/TN1S) using a custom-made jig consisting of a three-jaw drill chuck (Type 136S; Roehm, Sontheim, Germany) for mounting the post. The drill chuck was attached by a ball bearing to the upper moving part of the machine to allow free adjustment and alignment of the sample during the testing procedure. The embedded part of the sample was placed under a clamp and attached to the lower steady part of the machine (Fig. 1). The bond strength test was performed at a cross-head speed of 5 mm per min, until the post was dislodged from the cavity. The maximum pull-out force for each sample was recorded in *N*. To calculate the bond strength in MPa, we divided the pull-out force by the bonding area.

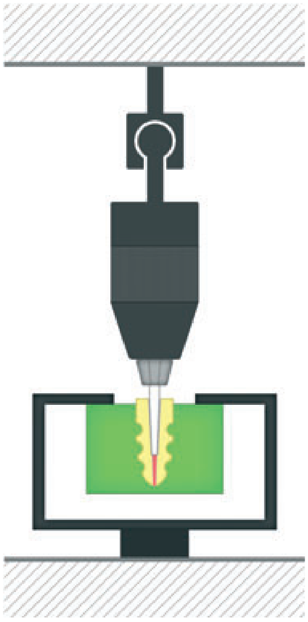


Fig. 1. Schematical illustration of the pull-out test design.

Failure mode assessment

The embedding resin was removed from the roots. After preparing longitudinal predetermined breaking lines onto the root surface using a diamond disk (947D), the roots were split in half. For failure mode assessment, the two halves and the post of all samples were analyzed under a stereomicroscope (Stemi CV; Zeiss, Jena, Germany). The following five failure modes were defined and the results were expressed in percentages: failure within the root dentin, failure between the dentin and the luting system, failure within the luting cement, failure between the luting system and the post, and failure within the post. The mean for the failure types (%) for each tooth was calculated by using the results from the two root halves and the post.

Statistical analysis

Data were recorded with acquisition sheets and transferred to IBM SPSS Statistics 19.0 (IBM Corp., Somers, NY, USA) for statistical analysis. For descriptive analysis, the bond strengths in MPa were graphically displayed in box plots. The results of the failure mode analysis were processed and shown in stacked bar charts. The Kolmogorov–Smirnov test (KST) was used to test the data for normal distribution; normally distributed data were evaluated with parametric tests. The level of significance was set at $\alpha = 0.05$. For multiple testing, the Bonferroni–Holm procedure (BHP; $\alpha' = \alpha/$number of tests) was used to offset the α-error accumulation. For testing the influence of the post pretreatment, the *t*-test (TT) was used. To test the influence of the luting system type and the selection of the specific luting system, we conducted an analysis of variance (ANOVA). When ANOVA indicated statistically significant differences ($P < 0.05$) and the Levene's test demonstrated no equality of variances ($P < 0.05$), we conducted the Dunnett T3 *post-hoc* test (DT3) to compare the different luting system types as well as the luting systems. For comparing the bond strengths of the two luting systems within one luting system type, the TT was applied with BHP.

Results

Part 1: Influence of post pretreatment on bond strength between FRCPs and various adhesive luting systems

The data for all groups were normally distributed (KST; $P > 0.05$). Pretreatment of the post surface with an adhesive significantly influenced the bond strength (TT; $P < 0.001$). Pretreatment of the post with the respective adhesive system significantly increased the bond strength in all four groups (MLP_ML, A_MCF, SBU_CC, LB_LCZ: TT; $P < 0.001$; BHP $\alpha' = 0.013$) compared to the posts that were only cleaned with alcohol (Fig. 2).

Part 2: Influence of luting system selection on the bond strengths of FRCPs conventionally or adhesively luted to bovine root canal dentin

Luting system types

The bond strength data for the various luting system types were normally distributed (KST; $P > 0.05$). ANOVA revealed a significant influence of the luting system type on the bond strength (Fig. 3; $P < 0.001$). Pairwise comparison of the bond strengths (Table 5) indicated significant differences (DT3; $P < 0.001$) between the conventional systems [CGIC_co, conventional glass ionomer cement (CGIC), RRGIC (resin-reinforced glass-ionomer cement)] and the adhesive luting systems [self-adhesive resin cement (SARC), self-conditioning adhesive + resin cement (SCA + RC), etch and rinse adhesive + resin cement (ERA + RC)]. The predominant failure for the conventional luting systems as well as for the etch-and-rinse adhesive plus resin cement

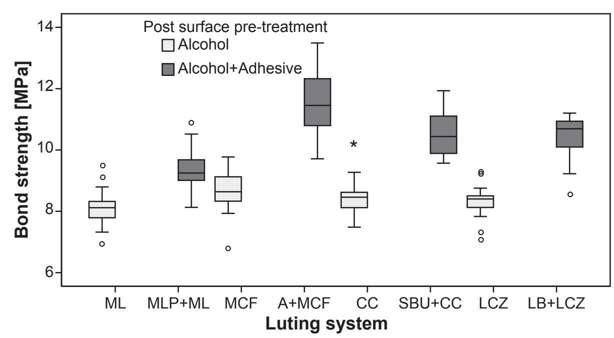


Fig. 2. Pull-out bond strength [MPa] between fiber-reinforced composite posts (FRCP) and adhesive luting systems*, depending on the post pretreatment procedure. MPL, Multilink Primer; ML, Multilink; A, AdheSE + DC Acticator; MCF, MultiCore Flow; SBU, SealBond Ultima; CC, CoreCem; LB, LuxaBond; LCZ, LuxaCore Z; *The box (IQR, interquartile range) represents the 25th to 75th percentile, the whiskers show the minimum and maximum, except for outliers (dots; 1.5–3 times of the IQR) and extreme values (asterisk; more than three times IQR).

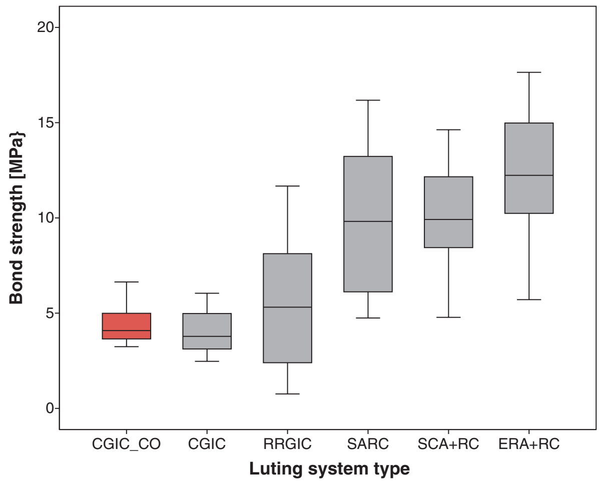


Fig. 3. Pull-out bond strength [MPa] of conventionally and adhesively luted posts to bovine root canal dentin*, depending on the luting system type. CGIC_co, conventional glass-ionomer cement; control with titanium post; CGIC, conventional glass-ionomer cement; RRGIC, resin-reinforced glass-ionomer cement; SARC, self-adhesive resin cement; SCA + RC, self-conditioning adhesive + resin cement; ERA + RC, etch and rinse adhesive + resin cement. *The box (IQR, interquartile range) represents the 25th to 75th percentile, the whiskers show the minimum and maximum, except for outliers (dots; 1.5–3 times of the IQR) and extreme values (asterisk; more than three times IQR).

occurred between the luting system and the post. The main failure for the SARC occurred between the luting system and the dentin (Fig. 4).

Luting systems

The bond strength data for all luting system groups were normally distributed (KST; $P > 0.05$), motivating the use of parametric tests. The selection of the luting system significantly influenced the bond strength (ANOVA; $P < 0.001$). The comparison of the luting systems with the control (KC_co) revealed statistically significant differences (DT3; $P < 0.05$) for all groups except the KC and BC groups (Fig. 5 and Table 6). With the exceptions of MP (2.3 ± 1.0 MPa) and KC

Table 5. Luting system type – comparison of bond strength

CGIC_co	CGIC	RRGIC	SARC	SCA + RC	ERA + RC	
	0.999	0.984	0.000	0.000	0.000	CGIC_co
		0.805	0.000	0.000	0.000	CGIC
			0.008	0.000	0.000	RRGIC
				1.000	0.140	SARC
					0.249	SCA + RC
						ERA + RC

P-values of pairwise comparison (bond strength) of the luting system types using Dunnett T3 *post-hoc* test. Gray fields display statistically significant differences.

CGIC_co, conventional glass-ionomer cement; control group with titanium post; CGIC, conventional glass-ionomer cement; RRGIC, resin-reinforced glass-ionomer cement; SARC, self-adhesive resin cement; SCA + RC, self-conditioning adhesive + resin cement; ERA + RC, etch and rinse adhesive + resin cement.

(4.0 ± 1.1 MPa), all luting systems generated higher bond strengths than the control (KC_co: 4.4 ± 1.1 MPa). The highest bond strengths were measured in luting system groups RXU (12.0 ± 3.0 MPa) and LB_LCZ (14.8 ± 2.3 MPa). The failure mode analysis showed similar distributions for all groups, with the predominant failure occurring between the luting system and the post except for groups RXU, BC, and A_MCF; in these groups, the main failure occurred between the dentin and the luting system (Fig. 6).

Luting systems within one luting system type

We compared the respective luting systems within a single luting system type (Fig. 5 and Table 7). Significant differences (TT with BHP ($\alpha' = \alpha/4 = 0.013$); $P \leq 0.001$) were uncovered for RRGIC, SARC, and BHC + RC, but not for SCA + RC (TT with BHC ($\alpha' = \alpha/4 = 0.013$); $P = 0.470$). Fracture analysis of the luting systems by luting system type showed similar failure distributions except for SCA + RC (Fig. 6).

Discussion

Methodological factors

Bovine teeth were selected as substrates for the present study because of standardized conditions in size, age, and storage time. All samples were caries-free, freshly extracted, and straight rooted, while human teeth exhibit a great variety in anatomical structure (31) and sometimes must be stored for extended periods in chemical solutions until the required number of teeth have been collected. Opinions on the use of bovine or human dentin substrate differ in the literature. While some authors reject the use of bovine teeth due to

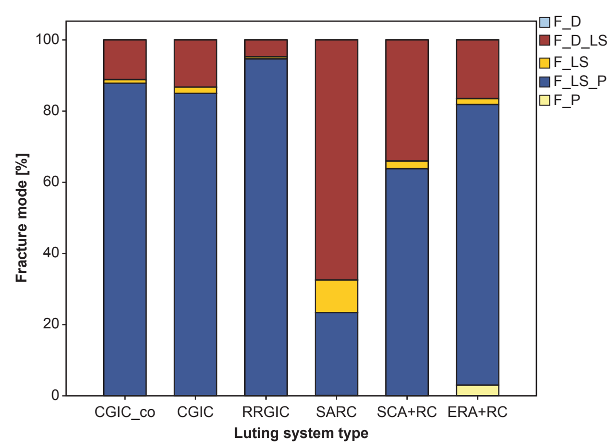


Fig. 4. Failure mode analysis [%] of conventionally and adhesively luted posts to bovine root canal dentin, depending on the luting system type. CGIC_co, conventional glass-ionomer cement; control with titanium post; CGIC, conventional glass-ionomer cement; RRGIC, resin-reinforced glass-ionomer cement; SARC, self-adhesive resin cement; SCA + RC, self-conditioning adhesive + resin cement; ERA + RC, etch and rinse adhesive + resin cement.

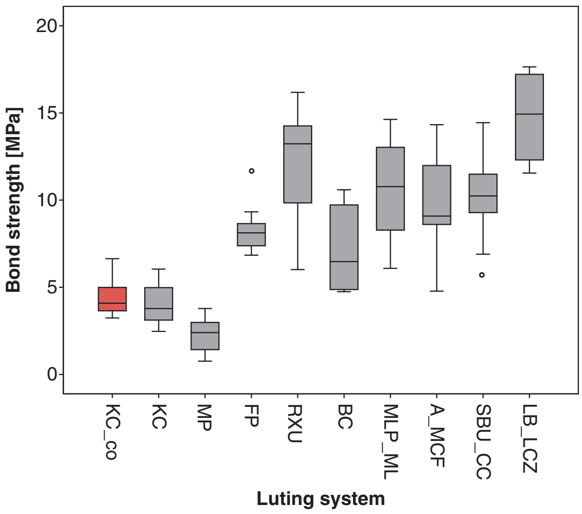


Fig. 5. Pull-out bond strength [MPa] of conventionally and adhesively luted posts to bovine root canal dentin*, depending on the luting system. CGIC, conventional glass-ionomer cement; RRGIC, resin-reinforced glass-ionomer cement; SARC, self-adhesive resin cement; SCA + RC, self-conditioning adhesive + resin cement; ERA + RC, etch and rinse adhesive + resin cement; KC_co, Ketac Cem control with titanium post; KC, Ketac Cem; MP, MeronPlus; FP, Fuji Plus; RXU, RelyX Unicem; BC, BisCem; MPL_ML, Multilink Primer and Multilink; A_MCF, AdheSE and MultiCore Flow; SBU_CC, SealBond Ultima and CoreCem; LB_LCZ, LuxaBond and LuxaCore Z. *The box (IQR, interquartile range) represents the 25th to 75th percentile, the whiskers show the minimum and maximum, except for outliers (dots; 1.5–3 times of the IQR) and extreme values (asterisk; more than three times IQR).

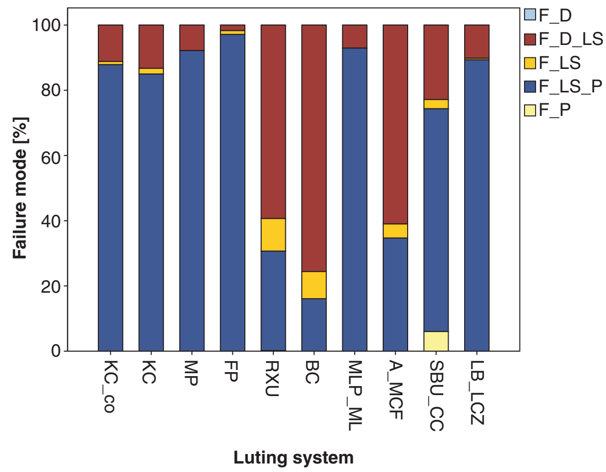


Fig. 6. Failure mode analysis (%) of conventionally and adhesively luted posts to bovine root canal dentin, depending on the luting system. CGIC, conventional glass-ionomer cement; RRGIC, resin-reinforced glass-ionomer cement; SARC, self-adhesive resin cement; SCA + RC, self-conditioning adhesive + resin cement; ERA + RC, etch and rinse adhesive + resin cement; KC_co, Ketac Cem; control with titanium post; KC, Ketac Cem; MP, MeronPlus; FP, Fuji Plus; RXU, RelyX Unicem; BC, BisCem; MPL_ML, Multilink Primer and Multilink; A_MCF, AdheSE and MultiCore Flow; SBU_CC, SealBond Ultima and CoreCem; LB_LCZ, LuxaBond and LuxaCore Z

differences in dentin structure such as the number of dentin tubules (32, 33) or differences in bond strengths (34), other studies demonstrated similar results for both types of substrate (35–37). However, most studies that compared the bond strengths of bovine and human dentin were focused on coronal dentin (33, 37). In one study that addressed the bond strengths of adhesive luting systems on root canal dentin (34), the root canals were pretreated with only one adhesive system (All Bond 2) and filled with one resin cement (Duolink). For this specific luting system, statistically significant differences were found between the two substrates. Another study, presented at the annual meeting of the International Association of Dental Research in 2011 (38), revealed no significant differences in bond strength when using bovine or human root canal dentin for posts luted with glass-ionomer cement, resin-modified glass-ionomer cement, or SARCs. Statistically significant differences were detected following the use of self-conditioning adhesives or etch-and-rinse adhesives in combination with resin cements. With this knowledge in mind, the bond strengths measured in our

Table 6. Luting system – comparison of bond strength

KC_co	KC	MP	FP	RXU	BC	MPL_ML	A_MCF	SBU_CC	LB_LCZ	
	1.000	0.009	0.000	0.000	0.194	0.001	0.008	0.001	0.000	KC_co
		0.069	0.000	0.000	0.086	0.000	0.004	0.000	0.000	KC
			0.000	0.000	0.003	0.000	0.000	0.000	0.000	MP
				0.122	0.975	0.593	0.997	0.814	0.000	FP
					0.026	1.000	0.935	0.991	0.614	RXU
						0.157	0.668	0.263	0.000	BC
							1.000	1.000	0.053	MPL_ML
								1.000	0.017	A_MCF
									0.019	SBU_CC
										LB_LCZ

P-values of pairwise comparison (bond strength) of the luting systems using Dunnett T3 *post-hoc* test. Gray fields display statistically significant differences. KC_co, Ketac Cem, control group with titanium post; KC, Ketac Cem; MP, MeronPlus; FP, Fuji Plus; RXU, RelyX Unicem; BC, BisCem; MPL_ML, Multilink Primer and Multilink; A_MCF, AdheSE and MultiCore Flow; SBU_CC, SealBond Ultima and CoreCem; LB_LCZ, LuxaBond and LuxaCore Z.

Table 7. Luting system per luting system type – comparison of bond strength

Luting system type	Comparison luting system	*T*-test
RRGIC	MP vs FP	0.000
SARC	RXU vs BC	0.001
SCA + RC	MLP_ML vs A_MCR	0.470
ERA + RC	SBU_CC vs LB_LCZ	0.000

P-values of pairwise comparison (bond strength) of the luting systems per luting system type using *t*-test with Bonferroni-Holm procedure ($\alpha' = 0.013$). Gray fields display statistically significant differences.
RRGIC, resin-reinforced glass-ionomer cement; SARC, self-adhesive resin cement; SCA + RC, self-conditioning adhesive + resin cement; ERA + RC, etch and rinse adhesive + resin cement; MP, MeronPlus; FP, Fuji Plus; RXU, RelyX Unicem; BC, BisCem; MPL_ML, Multilink Primer and Multilink; A_MCF, AdheSE and MultiCore Flow; SBU_CC, SealBond Ultima and Core-Cem; LB_LCZ, LuxaBond and LuxaCore Z.

study should be used to describe tendencies and should not be uncritically transferred to human substrate.

Each sample was endodontically treated. To simulate the clinical situation, sodium hypochlorite (5.25%) and citric acid (40%) were used for intermittent root canal irrigation (39). Roots were filled with gutta-percha and AH plus as a standard protocol (5, 40–42). During the preliminary tests for this study, the root canals were filled with gutta-percha up to the cemento-enamel junction. During post cavity preparation, the post drills squiggled when removing the softened gutta-percha, with the result that in some cases, the post cavities were enlarged and therefore wider than the posts. In addition, when controlling the post cavity walls under the dental operating microscope, we observed gutta-percha remnants along the dentinal walls in some specimens. Therefore, the root canals were filled sectionally only in the apical part to avoid altering the bond strengths via gutta-percha remnants. After allowing the sealer to set, the post cavities were prepared with the respective pilot drills. Rinsing with sodium hypochlorite is known to significantly reduce the bond strengths of adhesive luting systems (43, 44). Therefore, after finishing the post cavity preparation, we used sterile distilled water instead of sodium hypochlorite for irrigation.

Taking the observations and studies of the last two decades into consideration, the use of FRCPs in combination with chemical or dual-cured adhesive luting systems seems to be the method of choice for restoring endodontically treated teeth with extensive coronal hard tissue loss (14, 15, 19). For the treatment of traumatized incisors requiring endodontic therapy, both the survival of the tooth and the esthetical outcome are of great interest. For young patients in particular, who present immature teeth with thin root canal walls, the survival rate of the teeth not only depends on successful endodontic treatment but also on an adequate restorative concept. Thin root canal walls are prone to an increased fracture risk in the cervical region (45–48). Long-term intra-canal dressing with calcium hydroxide during the apexification procedure can increase the fracture risk (45). These cervical root fractures can be often fatal for the tooth because of an unfavorable subgingival or subcrestal localization (46, 48).

The use of adhesively luted FRCPs may help to decrease the fracture risk by creating a stabilizing monoblock between the root canal wall, the luting system, the post, and the build-up (11, 16–18); the similar modulus of elasticity of FRCPs and dentin supports the monoblock theory (49, 50). We used a tapered quartz FRCP with superior mechanical properties for this study (51, 52). The posts were individually manufactured by RTD to match the surface roughness of the TiP used in this study. TiPs were chosen as the control in this study because they have been successfully used in the clinical situation for decades in combination with zinc phosphate or glass-ionomer cements (6–8). Due to the similar surface roughness of the FRCP and the TiP, the post surface roughness can be neglected as an influencing factor on bond strength in this study.

A wide variety of materials are available for luting posts to root canals. The efforts of the dental industry follow the requirements of dentists to simplify the materials in terms of technique sensitivity, time of exposure, and material costs. However, simplified materials sometimes do not achieve outcomes equal to those for more complex materials, especially for adhesive systems (15). Therefore, we systematically included different material types with various mechanisms of action and a progressive degree of simplification to evaluate the influence of the luting system selection on the bond strength. As a control, we luted the TiP with conventional glass-ionomer cement, a technique that has been successfully used in clinical situations for decades (6–9). As the retention of metal posts proved to be predominantly sufficient in clinical performance (6, 9), and because the mechanical properties of the particular FRCP used in this study are equal or superior to metal posts (51, 52), we included conventional luting systems (conventional and resin-reinforced glass-ionomer cement) for inserting the FRCPs in our testing procedure. In addition to conventional luting systems, we selected two commonly used brands of each of the adhesive luting system types. Etch-and-rinse adhesive with resin cement was included as the most complex luting system type, followed by self-conditioning adhesive with resin cement as a system with intermediate complexity, and self-conditioning resin cements as the simplest luting system type.

The interface between the luting system and the post surface of the prefabricated FRCPs is the weakest link in the monoblock system consisting of the tooth, the luting system, and the post (23). FRCPs are usually manufactured by lathing the post shape out of a completely polymerized fiber-composite blank. The machine-processed post surface therefore most likely does not provide free radicals for chemical bonding to the luting system components. For these types of FRCPs, mechanical retention is the predominant mechanism for bonding the luting system to the post surface. Several recent studies have focused on increasing the retention properties of the luting systems by conditioning the post surface (22–27). The methods are based on either improving the mechanical retention by etching (24) or sandblasting (24, 25) or on establishing a chemical bond by silicatization and/or silanization (26, 27). Some of these methods such as sandblasting and silicatization require special equipment that is not available in all dental offices.

We sought to improve the wetting of the post surface by pretreating the FRCPs with the respective adhesive systems for the self-conditioning and etch-and-rinse adhesives. We hypothesized that low-viscosity adhesives could penetrate the micro-retentions on the post surface better than the higher-viscosity resin cements, resulting in increased wettability of the post surface. The Part 1 of this study, which focused on the influence of post pretreatment on bond strength, revealed significantly better results for the groups in which the post surface was pretreated with the respective adhesive system (Fig. 2). Various investigations have uncovered a significant influence of the luting system application method on bond strength (53, 54). Applying the luting cement bubble-free into the root canal with endodontic tips seemed to result in the highest bond strength. We previously observed that rolling the post with finger pressure in a luting cement reservoir to increase the wetting of the post before inserting it into the filled post cavity led to an additional increase in the bond strength (unpublished data from pilot experiments). We therefore included this surface pretreatment in the current study protocol.

Various methods are available for measuring bond strengths; the push-out design is very common and is considered to be precise. Several sections can be obtained from one tooth, allowing investigation of the bond strengths in different root regions (30). Due to the conical post shape, side load and notch stress can be minimized while the bond strengths are higher than in other testing methods (28, 44). Disadvantages of this method include the time-consuming preparation of the thinly sliced samples and the dependency of bond strength on the localization of the push-out force (55). Another method for testing bond strength is the microtensile test, but the sample preparation is time-consuming and requires experience. When using this technique for testing bond strength between FRCPs and root canal dentin, the failure rate during sample preparation is higher than that for all other methods (29, 30). This method is not practical when testing luting systems such as conventional luting cements that generate low bond strength.

For the present study, the pull-out test was performed to evaluate tendencies in the bonding/adhesive performance of a broad variety of luting materials. An investigation comparing different bond strength test methods found that the pull-out test and a modified push-out test resulted in the highest number of samples with adhesive failure (28). The adhesion between the post and the luting system or the dentin and the luting system are the main points of interest when testing the bonding performance of luting systems; cohesive failure within the dentin or the post adulterates the test results. Pull-out tests permit the analysis of a large number of samples within an adequate time frame. In addition, the luting interfaces are not altered during the sample preparation, as is the case for push-out or microtensile testing. Especially for luting systems, generating low bond strengths (as with conventional cements), the vibration during the sectioning procedure may partly disintegrate the cement structure and negatively influence the results of the bond strength testing. Another application of the pull-out test seems to be the testing of posts with macro-retentive surface designs. The lack of a failure analysis (56, 57) and restricting the analysis to the post (53, 58) during a pull-out bond strength test are disadvantages compared to the push-out and microtensile tests, where it is easier to carry out fracture analysis of all components. To overcome this problem, we sectioned the teeth longitudinally to allow failure analysis of the post as well as of the two tooth halves.

Study outcomes

Part 1: Influence of post pretreatment on bond strength between FRCPs and adhesive luting systems

The null hypothesis of this part of our study was rejected. We observed that pretreating the surface of FRCPs with the various adhesive systems significantly affected the bond strengths. The increase in bond strength between the post and the luting system can be explained by the low viscosity of the adhesive, which improved the wetting and penetration of the post surface's microrelief and therefore optimized the micro-interlocking interaction between the post surface and the luting system (59).

Part 2: Influence of luting system selection on the bond strengths of FRCPs conventionally or adhesively luted to bovine root canal dentin

We investigated whether the various types of conventional luting systems generated similar bond strengths compared to adhesive luting system types when used for post insertion. The null hypothesis was rejected; in general, the more complex luting system types led to higher bond strengths than the simplified systems (Fig. 3 and Table 5; CGIC < RRGIC < SARC < SCA + RC < ERA + RC). The comparison of conventional (CIGIC and RRGIC) and adhesive luting systems (SARC, SCA + RC, ERA + RC) demonstrated that adhesive luting systems showed favorable results in terms of bond strength. When comparing the test groups (FRCP luted with CGIC, RRGIC, SARC, SCA + RC, and ERA + RC) with the control group (CGIC_co; TiP luted with CGIC), the adhesive luting systems exhibited significantly higher bond strengths. The bond strengths of the FRCPs luted with conventional luting systems did not differ from those of the control group, perhaps because conventionally luted posts mainly rely on friction for retention while adhesively inserted posts predominantly bond chemo-mechanically to the root canal dentin (14). Regarding the interface between the post and the luting system, all luting systems rely on mechanical retention to the post. As the surface roughness of the FRCP and the TiP are similar, the bond strengths of all groups can be compared. Another reason for the superior performance of the adhesive luting systems may be based on post surface properties for water acceptance. The components of FRCPs are even more hydrophobic than those of the TiPs and the resin-based luting systems, while glass-ionomer cements and dentin are considered hydrophilic. Therefore, the wettability of the hydrophobic post surfaces may be impaired by differences in polarity when using hydrophilic glass-ionomer cement for luting, while the similar polarities that accompany the use of hydrophobic resin-based adhesive luting systems should result in superior wettability of the hydrophobic post material.

For conventional luting systems (CIGIC and RRGIC), the failure analysis (Fig. 4) indicated predominant failure (85–95%) between the post and the luting system at relatively low bond strengths (4.0–5.3 MPa). This observation supports the theory that the bonding performance of glass-ionomer cement to hydrophobic post surface is inferior. In contrast, chemical linkage of glass-ionomer cements to the hydrophilic dentin via calcium ions seems to be stronger. However, the failure analysis also revealed predominant failure between the post and the luting system for SCA + RC (64%) and ERA + RC (79%), but at distinctly higher bond strengths compared to conventional luting systems. In these cases, the chemo-mechanical bonding of the luting system to the root canal dentin was superior to mechanical retention of the luting system to the post surface by micro-interlocking. In contrast, the predominant failure mode (67%) for SARC occurred between the dentin and the luting system. These differences may be explained by varying mechanisms of bonding to the dentin. With etch-and-rinse adhesives, the smear layer should be completely removed and a hybrid layer and distinctive resin tags should be generated; self-conditioning adhesives only modify the smear layer and form a hybrid layer and smaller resin tags. The smear layer should also be modified in the case of SARCs, and the resulting hybrid layer is reduced compared to more complex adhesive systems (30). Therefore, the bonding of the SARC to the post seems to be greater than SARC's bonding ability to dentin.

Our second hypothesis in Part 2 of our study stated that the selection of the luting system does not influence bond strength; the null hypothesis was rejected. Most luting systems exhibited significantly higher bond strengths than the control group, except for the KC and BC groups. MP showed significantly inferior bond strength than the control group (Fig. 5 and Table 6), which may have been due to the MP mixing mechanism. While all other materials were pre-dosed to ensure similar mixing conditions with each application, the MP powder and fluid were dosed from the package and individually mixed by hand. The conventional luting systems gave inferior results compared to the adhesive luting systems, except for FP. FP generated results that were statistically similar to the adhesive luting systems, except for LB_LCZ, and distinctively higher results compared to all other conventional luting systems. This superior performance of FP may be due to the conditioning of the dentin with a mild acid to remove the smear layer, which may improve the chemical bonding of the glass-ionomer component of FP directly to the dentin via calcium ions in the absence of an intermediate smear layer (60–62). The luting systems exhibiting the highest bond strengths were the simplified single-step SARC RXU (12.0 ± 3.0 MPa) and the more complex multi-step ERA + RC LB_LCZ (14.8 ± 2.3 MPa), observations that are consistent with previous studies (30, 38, 63). However, the smaller standard deviation of the LB_LCZ groups indicates lower technique sensitivity compared to RXU, in combination with reproducible high bond strengths. The failure analysis revealed different predominant failure modes (RXU: 59% between the luting system and the dentin; LB_LCZ: 89% between the luting system and the post), as expected due to the different bonding mechanisms of SARC and ERA + RC to dentin.

We demonstrated that the luting system type was not necessarily responsible for the bonding performance. Comparison of the luting systems within their respective luting system types (Fig. 6 and Table 7) revealed significant differences between all groups, except for SCA + RC (MLP_ML vs A_MCF). Nearly identical bond strengths were measured for the two glass-ionomer luting groups (CGIC_co and CGIC), and the failure modes were comparable. In both groups, the luting system (KC) and the post surface roughness were similar; only the post material (fiber-reinforced composite vs titanium) varied, suggesting that the bond strengths should be similar.

The bond strengths generated by the two tested luting systems within the RRGIC type differed distinctly (MP: 2.3 ± 0.9 MPa; FP: 8.3 ± 1.3 MPa). In the manufacturer's instructions, MP is indicated for cementation of indirect metal restorations, but its use for luting FRCPs is not indicated. MP is considered a hydrophilic resin-reinforced cement, which may counteract appropriate bonding to the hydrophobic post material. The discrepancy between FP and MP may be due to the different application modes: MP was measured and mixed by hand without any pretreatment of the root canal dentin surface, while FP comes in standardized capsules. Before inserting the post with FP, the root canal dentin was pretreated with Fuji Plus Conditioner to remove the smear layer. A better chemical bonding of glass-ionomer cement to dentin may be achieved by root canal conditioning when using weak acids (64, 65). The advantages of FP include less sensitivity to technique and a smaller time commitment, but the system achieves bond strengths comparable to most of the tested adhesive luting systems (except for LB_LCZ). However, the indication for using RRGIC for luting endodontic posts should be critically discussed and needs further evaluation. RRGIC is known for water sorption and consequent expansion of the material (66, 67), which could theoretically lead to vertical root fractures when used in root canals. This consideration can only be neglected if absolutely no water can access the luting material around the cemented post.

Regarding the SARC luting system, RXU achieved distinctively higher bond strengths (12.0 ± 3.0 MPa) than BC (7.00 ± 2.3 MPa). RXU is one of the most investigated SARCs (68), and RXU exhibits a bond strength similar to multi-step systems in luting FRCPs to root canal dentin (53, 69, 70). The adhesion mechanism is known to rely on both micromechanical retention and chemical bonding (68, 69). Gerth et al. (71) reported that the chemical interaction of RXU with hydroxyapatite was responsible for the mechanical properties and the good bond strength of the product. These observations were confirmed by the present study. RXU may therefore be favored for luting posts in the clinical situation, when no core built-up is required, due to its easy application mode and its good bonding performance.

The two materials tested within the SCA + RC luting system type did not generate significantly different bond strengths (MLP_ML: 10.6 ± 2.7 MPa, A_MCF: 9.7 ± 2.9 MPa). Self-conditioning adhesive systems combine the conditioning and the bonding step, and they modify the smear layer without removing it. The superficially exposed dentinal collagen fibers are simultaneously coated with amphiphilic monomer and resin, resulting in less uncovered collagen compared to dentin etched with strong acids, which can decrease nano-leakage (72–74). In our study, the one-step adhesive MLP in combination with ML generated bond strength similar to the more complex two-step adhesive A in combination with MCF. Therefore, for clinical application, MLP_ML seems to be more recommendable from a practical point of view.

For ERA + RC, LB_LCZ achieved the highest bond strength in this study. The bond strengths of LB_LCZ (14.8 ± 2.3 MPa) and SBU_CC (10.2 ± 2.6 MPa) were significantly different. For both luting systems, the smear layer is removed by a separate etching step; therefore, in addition to the creation of a hybrid layer, the adhesive can penetrate the exposed and opened dentinal tubules to form resin tags for additional retention. The differences in bond strength may be due to the composition of the adhesive. SBU is a one-bottle adhesive that is applied two times consecutively for priming and adhesive application. LB consists of a Pre-Bond (polymerization enhancer) and a two-bottle one-step adhesive. However, the results for ERA + RC should be critically examined when using bovine teeth as a substrate, because the partially different dentin structure and the wider dentinal tubules may lead to increased bond strength (38).

Use of the more complex etch-and-rinse system LB_LCZ and the simplified RXU led to bond strengths that exceeded the other systems. Similar results were reported by another study on human teeth (38). For clinical application in cases requiring an additional core build-up, we recommend the use of LB_LCZ to create a monoblock within the post and the build-up. RXU is indicated for adhesively luting posts to the root canal but not for core build-up.

Clinical application

The endodontic, periodontal and restorative treatment was performed by Dr. C. Berthold (FAU Erlangen-Nuernberg, Dental Clinic 1 – Operative Dentistry and Periodontology). The orthodontic procedure was carried out by PD Dr. A. Holst (FAU Erlangen Nuernberg, Dental Clinic 3 – Orthodontics).

A 9-year-old male patient suffered a dental injury after falling from his bike on the way to school. Emergency treatment after the injury was carried out by his dentist and consisted of an initial endodontic treatment of the fractured central incisors and flexible splinting of the laterally dislocated and loosened left central incisor (tooth 21). Two weeks after the injury, the patient was referred to our clinic for further treatment of both central incisors, with the questions of if and how the fractured right central incisor (tooth 11) could be restored.

The patient was examined, and diagnoses were framed with the information from the referring dentist. Tooth 11 was diagnosed with a crown-root fracture with pulp exposure and extensive hard tissue loss. Tooth 21 was diagnosed with lateral dislocation combined with enamel–dentin fracture. At the time of examination, the flexible splint was *in situ* and the endodontic treatment of both central incisors had already been initialized with intra-canal calcium hydroxide dressing. Tooth 11 showed a distinct gray discoloration (Fig. 7). The access cavity of tooth 11 was only sealed with Cavit, while the access of tooth 21 was sealed with composite. A cervical root fragment remained *in situ* on the palatinal aspect of tooth 11 (Fig. 8).

Treatment planning resulted in an interdisciplinary approach. After removing the splint and finishing the endodontic treatment of both central incisors as well as adhesively sealing the access and the exposed dentinal surface, tooth 11 was orthodontically extruded (Figs 9 and 10) and the gingiva level was later adapted by periodontal surgery. After internal bleaching of the discolored tooth 11, the patient received a temporary adhesively bonded composite build-up on tooth 11 until the completion of the orthodontic aligning of all teeth.

The patient approached the clinic again at age 14 when he lost part of the temporary composite build-up on tooth 11 after accidently hitting the tooth with a bottle. Orthodontic therapy had been finalized 2 years before this appointment. Therefore, we approached the previously planned definite restoration consisting of an adhesively luted FRCP in combination with a direct

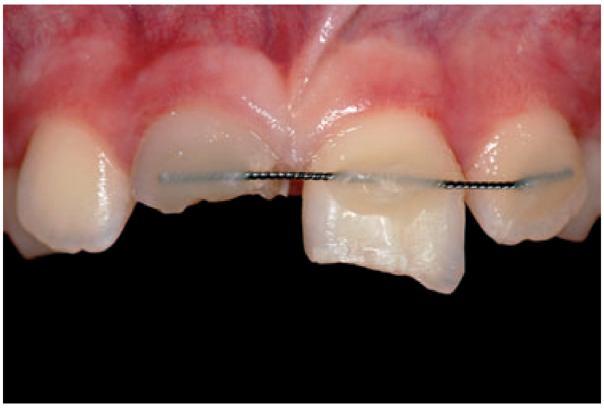


Fig. 7. Situation 2 weeks after the injury with fractured maxillary central incisors and the flexible wire composite splint *in situ*.

Fig. 8. Oral view after splint removal shows the gray discoloration of tooth 11 and the partly lost temporary filling. Palatinal, the tooth fragment, remaining from the crown-root fracture, is still *in situ*.

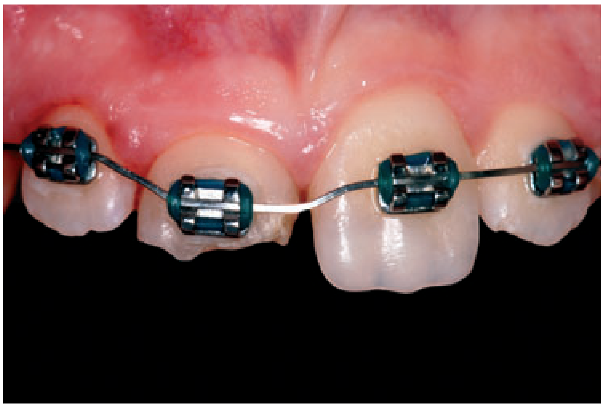


Fig. 9. Orthodontic appliance for extrusion of the fractured tooth 11. The soft tissue moved with the tooth, recognizable by the different gingiva level of the central incisors. Surgical gingiva modulation is indicated to improve the esthetical outcome.

composite build-up. The FRCP was introduced to reinforce the thin root canal walls and to improve the retention of the composite build-up.

An individual mock-up was shaped with composite (Tetric Ceram, Ivoclar Vivadent, Schaan, Liechtenstein) on teeth 11 and 21 to prepare a silicon template (Elite Tranparent; Zhermack, Badia Polesine, Italy) for shaping the palatinal part of the final restoration (Fig. 11). After removing the remaining composite, gutta-percha was gently removed at a length of 10 mm without additionally reducing the thin root canal walls. The prefabricated FRCP size 6 (investigated in the current study) was adapted to the desired length and fitted to the root canal. Due to the extensive width of the root canal, no primary retention could be achieved between the post and the canal walls (Fig. 12). However, when filled with resin cement, wider gaps between the post and the root canal walls do not seem to alter the performance of adhesively luted FRCPs (75, 76). The post surface was cleaned with alcohol before the luting procedure.

Fig. 10. Six month radiographic control of root canal filling, immediately after removal of the orthodontic extrusion appliance. The root canal filling is covered with glass-ionomer cement and the coronal pulp camber is filled with calcium hydroxide for neutralization after bleaching. The apical translucency on tooth 11 indicates the extrusion distance. The tooth was fixated to retain the extrusion result.

Fig. 11. Mock-up situation of for the central incisors with Tetric Ceram to prepare the silicon template for direct composite restoration.

We selected LB in combination with LCZ based on the observations of the current investigation. The post cavity was conditioned with Etching Gel. After removing the phosphoric acid gel by intensive irrigation with sterile distilled water, the post cavity was dried. The post cavity was then re-wetted according to the manufacturer's instructions, a step that is necessary and important for re-erecting the collapsed collagen fiber network to ensure optimal penetration of the acetone-based adhesive system. PreBond and the mixture of Bond A and Bond B were then applied to both the post cavity and the post surface, in accordance with the manufacturer's instructions for dentin. While filling the post cavity with LCZ, the post was rolled in a luting material reservoir on a mixing pad to achieve optimal wetting of the post surface. The FRCP was inserted into the post cavity, excess resin cement was removed, and polymerization of the dual-cured luting system was initialized with light (2000 mW cm^{-2}; Mini

Fig. 12. Try-in of the fiber-reinforced composite posts (FRCP) size 6, after partial gutta percha removal.

LED III; Satelec Acteon Equipment, Merignac, France).

The dentin and enamel surface were then prepared for the composite build-up with finishing drills followed by total etching (Etching Gel) and application of the dentin/enamel bonding (Syntac; Ivoclar Vivadent). The palatinal part of the restoration was shaped using the prepared transparent silicon template (Fig. 13). The dentin core was modeled in consecutive layers using differently colored, opaque dentin masses (Fig. 14), the incisal edge was individualized by transparent masses, and the restoration was finalized by placing the enamel mass (Amaris, VOCO, Cuxhaven, Germany). The build-up of tooth 21 was accomplished in a similar fashion. The restorations were preliminarily shaped, finished, and polished to allow recovery of the color of the dried-out enamel. A radiograph was taken to validate the correct post position (Fig. 15). At the final appointment, the finishing and polishing of the restoration were completed (Fig. 16).

Conclusion

Within the limits of this *in vitro* study, we draw the following conclusions. Pretreating the posts with the various adhesive systems increased the bond strengths between the FRCP and the adhesive luting systems.

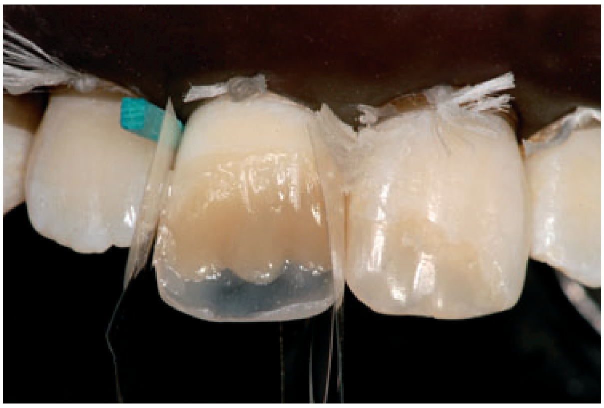


Fig. 14. Application of the first layer of opaque composite masses for dentin core built-up.

Fig. 15. Final radiograph control after post insertion and direct composite restoration of tooth 11. The endodontic treatment of both central incisors was conducted about 4 years ago. The root canal filling is adequate and no signs of inflammation detectable. The apical root tip of tooth 21 appears reduced by resorptions, possibly as a result of the previously applied orthodontic forces.

Fig. 13. Palatinal tooth facet reconstructed with composite by using the silicon template.

Fig. 16. Reconstructed central incisors after final finishing and polishing.

The type of luting system and the specific luting system both significantly influenced bond strength. Adhesively luted FRCPs achieved higher bond strengths than conventionally luted posts. The bond strengths of the two tested luting systems within one luting system type differed, except for SCA + RC. The adhesive luting systems RXU and LB_LCZ achieved the highest bond strengths in this study on bovine root canal dentin. For clinical applications, RXU can be recommended for post insertion, while LB_LCZ can be used for post insertion and additional core build-up. Further clinical trials are necessary to validate these results under *in vivo* conditions.

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