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Dietschi, Didier; Ardu, Stefano; Rossier-Gerber, Anne; Krejci, Ivo

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Adaptation of Adhesive Post and Cores to Dentin after in vitro Occlusal Loading: Evaluation of Post Material Influence

Didier Dietschi^a/Stefano Ardu^b/Anne Rossier-Gerber^c/Ivo Krejci^d

Purpose: Fatigue resistance of post and cores is critical to the long term behavior of restored nonvital teeth. The purpose of this in vitro trial was to evaluate the influence of post material physical properties on the adaptation of adhesive post and core restorations after cyclic mechanical loading.

Materials and methods: Composite post and cores were made on endodontically treated deciduous bovine teeth using 3 anisotropic posts (made of carbon, quartz, or quartz-and-carbon fibers) and 3 isotropic posts (zirconium, stainless steel, titanium). Specimens were submitted to 3 successive loading phases – 250,000 cycles at 50 N, 250,000 at 75 N, and 500,000 at 100 N – at a rate of 1.5 Hz. Restoration adaptation was evaluated under SEM, before and during loading (margins) and after test completion (margins and internal interfaces). Six additional samples were fabricated for the characterization of interface micromorphology using confocal microscopy.

Results: Mechanical loading increased the proportion of marginal gaps in all groups; carbon fiber posts presented the lowest final gap proportion (7.11%) compared to other stiffer metal-ceramic or softer fiber posts (11.0% to 19.1%). For internal adaptation, proportions of debonding between dentin and core or cement varied from 21.69% (carbon post) to 47.37% (stainless steel post). Debonding at the post-cement interface occurred only with isotropic materials. Confocal microscopy observation revealed that gaps were generally associated with an incomplete hybrid layer and reduced resin tags.

Conclusion: Regardless of their rigidity, metal and ceramic isotropic posts proved less effective than fiber posts at stabilizing the post and core structure in the absence of the ferrule effect, due to the development of more interfacial defects with either composite or dentin.

Keywords: adhesive post and cores, fiber posts, fatigue test, confocal microscopy, scanning electron microscopy.

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The large number of post designs and materials available on the market reflects an absence of consensus in the field of post and cores. Based on what the manufacturers or clinicians consider as the most important properties, posts can be fabricated either from gold, titanium, stainless steel,

or ceramic, or be resin-reinforced with several types of fibers. Fiber-reinforced resins^{9,10} and ceramic posts^{27,30,40,46,50} were developed to overcome the biomechanical and esthetic drawbacks of existing metal posts; they represent the most recent developments in this area and are today widely used. Clinical follow-ups and proof of satisfactory behavior are available for carbon-fiber posts and a few other white fibers,^{13,14,34,38} but there is a complete lack of evidence to support the use of ceramics as reinforcement in such substructures, especially for the buildup of severely decayed teeth.

The fracture resistance with or without cyclic mechanical loading showed that failures with fiber posts are less detrimental to the remaining tooth structure than more rigid posts made of metal or ceramic.^{19,20,28,49} Both in vitro and clinical studies have shown that root fracture is the major risk associated with rigid cemented posts, while debonding or post and core decementation are the most frequent prob-

^a Senior Lecturer, Department of Cariology and Endodontics, School of Dentistry, University of Geneva, Switzerland. Adjunct Associate Professor, Department for the Practice of General Dentistry, Case Western University, Cleveland, Ohio, USA.

^b Lecturer, Department of Cariology and Endodontics, School of Dentistry, University of Geneva, Switzerland.

^c Clinical Assistant, Department of Cariology and Endodontics, School of Dentistry, University of Geneva, Switzerland.

^d Professor and Chair, Department of Cariology and Endodontics, School of Dentistry, University of Geneva, Switzerland.

Reprint requests: Didier Dietschi, Dept. of Cariology and Endodontics, School of Dentistry, 19 Rue Barthélémy Menn, 1205 Geneva, Switzerland. Tel: +41-22-37-94-074, Fax: +41-22-37-94-102. e-mail: didier.dietschi@medecine.unige.ch

lems occurring with core buildup coupled to fiber posts. These findings therefore speak in favor of fiber posts and question the potential of more rigid isotropic metals and ceramic materials.

Clinical studies are difficult to carry out and their results are difficult to compare due to the number of uncontrollable variables and the absence of standardized clinical protocols and evaluation methods. Therefore, *in vitro* fatigue tests, which submit the specimens to cyclic mechanical loading, are increasingly applied to restored nonvital teeth in order to assess their biomechanical behavior.^{5,8,16,23,25,31,35} Such studies also have a clear advantage over classical monotonic fracture or tensile tests, which poorly reproduce physiological forces in terms of their direction and dynamics. Actually, they simulate an extreme mechanical and usually accidental stress, such as encountered in a trauma, while cyclic loading reproduces the most likely source of failure, which is the fatigue of materials and interfaces. In addition, a nondestructive evaluation protocol proved useful to compare the numerous existing restorative options as well as to identify the deficiencies of some materials and procedures.^{7,8,16} This method was established to monitor the marginal quality throughout the fatigue test and, after loading completion, to describe the micromorphology of the different internal adhesive interfaces.

Numerous fatigue studies have also confirmed the influence of post properties on the restoration behavior.^{7,25,26,35} For instance, it was shown that carbon-fiber posts, which exhibit physical properties close to natural dentin^{6,9} allow minimization of the incidence of adhesive failures or specimen fractures.^{7,35} Since the importance of basic physical post properties on the restoration quality and longevity is increasingly recognized, further research in this area is needed.

The aim of this *in vitro* study was to test the hypothesis that adaptation of adhesive post and cores, after mechanical loading, is influenced by the physical properties of the post material. An attempt was also made to characterize the adhesive interface between composite and dentin and to identify micromorphological characteristics which could be associated to continuous or defective interfaces.

MATERIALS AND METHODS

Sample Preparation

Fifty-four deciduous bovine teeth (lateral incisors) were used for this study. After collection, teeth were kept at 4°C in an isotonic sodium azide solution until the experiment began. Eight teeth were randomly assigned to each experimental group, corresponding to the different post materials (Table 1a).

The roots were first cut at 20 mm from the apex, opening the coronal third of the canal. The endodontic preparation was performed with manual instruments (Flexofile, Maillefer; Ballaigues, Switzerland) under 3% sodium hypochlorite irrigation. The canal was then filled with the largest fitting single gutta-percha point (standardized gutta percha points, Maillefer) together with a resin-based eugenol-free root canal cement (AH plus, Dentsply-DeTrey; Konstanz, Germany).

After a setting period of 48 h, samples were fixed on a metallic holder (Bal-Tec; Balzers, Liechtenstein) with self-curing acrylic resin (Technovit 4071, Heraeus-Kulzer; Wehrheim, Germany), embedding the first 12 mm of the roots. The roots were cut again at 15 mm from the apex in order to correspond to the root mean length of human front teeth (Marseillierx, 1952). The perpendicular root section created the core foundation. The post recipient was prepared according to the specific procedures and instruments of the Composipost system for post size No. 2 (RTD; St-Egrève, France). All posts (Composipost, Esthetipost and Estheti-plus; RTD), including experimental ones made of zirconium oxide, stainless steel, and titanium (RTD), had the same design, parallel stepped. The post insertion depth was fixed at 7.5 mm, corresponding exactly to the half of the root length. Post physical properties are described in Table 1a.

Restorative Procedures

Metal and zirconia posts were sandblasted with 50- μ m aluminous oxide powder at 2.5 bar pressure. Fibers posts were cleaned for 3 min in an ultrasonic bath with a 90% ethanol solution. The root canal and section surface were acid etched for 10 s with 35% H₃PO₄ gel (Ultraetch, Ultradent; South Jordan, UT, USA) before adhesive application (All Bond II primer A & B and a mixture of D/E resin and Prebond, Bisco; Schaumburg, IL, USA), following manufacturers' instructions. All posts were coated with Primer B (All Bond II) before luting with a self-curing composite (Coreflow, Bisco). A new layer of light-curing bonding resin (D/E resin) was then applied on the section surface and light cured for 40 s. The core was fabricated by applying several concentric 1.5-mm layers of a light-curing composite (Aelitfil A3.5, Bisco) up to 7.5 mm in height. The final core shape was established with cylindrical diamond burs under profuse water spray. Finishing and polishing consisted in refining the core margins with polishing disks (coarse to extra-fine Pop-on Sof-flex discs, 3M; St Paul, MN, USA) under 10X magnification with intermittent water spray. At completion, the core yielded a 1:1 ratio with the intraradicular portion of the post and exhibited a 45-degree plane (buccolingual) for contacting the artificial cusp of the fatigue device (Fig 1). The composition of adhesives and restorative materials is detailed in Table 1b.

Fatigue Test

The position of the artificial cusps in the test chambers of the mechanical fatigue device (Department of Restorative Dentistry and Endodontics, and Laboratory of Electronics of the Medical Faculty; University of Geneva) was adjusted to maintain a 1-mm distance to core top, allowing a free initial movement (Fig 1). The artificial cusps contacting the samples were made of stainless steel, the hardness of which is similar to natural enamel (Vickers hardnesses: enamel = 320 to 325; Actinit stainless steel = 315); they were designed with a slot to provide sample guidance and maintain its spatial relation with the device's central axis (Fig 1). Sample holders were themselves mounted on an inclined cylindrical rubber base, which allowed the restored teeth to undergo motion along the 45-degree path of the experimental device (Fig 1).

Table 1a Experimental groups and post systems under investigation. Physical characteristics of raw materials (manufacturers's data)

Groups	Basic constituents	tensile 30°	Modules tensile 45°	flexural	Tensile strength	Flexural strength
CC (Composipost)	Carbon fibers embedded in epoxy resin	17 to 18 GPa	11 GPa	145 GPa	2900 MPa	1900 MPa
CM (Aestheti-Plus)	Mineral fibers embedded in epoxy resin	15 GPa	10.6 GPa	44 GPa	2200 MPa	1150MPa
CH (Aesthetipost)	Mineral and carbon fibers embedded in epoxy resin	16.5 GPa	11 GPa	46 GPa	2500 MPa	1400 MPa
ZR (exp.)	Sintered zirconium oxide, machined	200 GPa	200 GPa	200 GPa	850 MPa	850 MPa
SS (exp.)	Stainless steel, machined	200 GPa	200 GPa	200 GPa	1200 MPa	1200 MPa
TI (exp.)	Titanium (Ti ₆ Al ₄ V), machined	110 GPa	110 GPa	110 GPa	1050 MPa	1050 MPa
dentin E-module = 2.4-2.7 10 ⁶ PSI / = 16.5-18.5 GPa; ⁶ enamel E-module = 80 GPa, dentine E-modulus = 18 GPa; ⁹ bovine dentin E-module = 13 GPa (RTD, 1997)						

Table 1b Adhesives and restorative materials under investigation

Material	Product name (manufacturer)	Composition (main constituents)	Application	Batch numbers
Conditioner	Ultraetch (Ultradent; Salt Lake City, UT, USA)	H ₃ PO ₄ 37% gel	10 s inside canal and on root section	-
	All-Bond 2 Primer A (Bisco)	acetone, ethanol, Na-tolyglycidyl methacrylate	5 coats mixture A/B on dentin	019108
dentin-bonding- agents	All-Bond 2 Primer B (Bisco)	acetone, ethanol, biphenyl dimethacrylate	5 coats mixture A/B on dentin	010158
	Pre-bond Resin (Bisco)	bisphenol diglycidylmethacrylate, benzoyl peroxide	one coat on post inside canal	079177
	D/E-Resin (Bisco)	bisphenol diglycidylmethacrylate	on root section light cured 40 s	019288
self-curing luting cement	Clore-Flo (Bisco)	filler: amorphous silica, alumina, glass resin: bisphenol diglycidylmethacrylate	inside canal + on post	089067 (catalyst) 089167 (base)
light-curing restorative material	Aelitefil (Bisco)	filler: Barium glass resin: Bis-GMA, UDMA, Polyakyleneglycol Dimethacrylate, Aminoakyl Methacrylate	1,0 mm increments around the post 40s light-curing per layer	A 3.5 029278

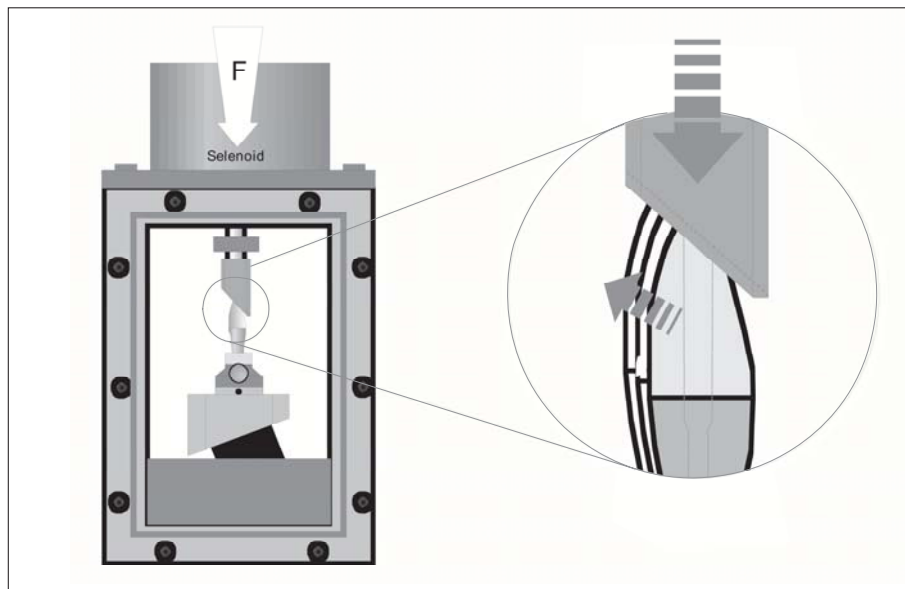


Fig 1 Schematized representation of a fatigue device chamber, with detailed description of the contact between the artificial stainless steel cusp and the core composite build-up and direction of the sample movements.

All samples were submitted successively to 3 mechanical loading phases (2 x 250,000 and 1 x 500,000 cycles) for a total of 1,000,000 cycles. The loading force generated by solenoids (Magnet; Hausen am Albis, Switzerland) was set at 50 N, 75 N, and 100 N, respectively, for the 3 successive experimental phases, with a 1.5 Hz frequency, and following a one-half sine-wave curve. The maximal force (for each phase) was attained at the end of a 2.5-mm total course of the solenoid cores (including the first 1 mm free displacement). The specimens remained immersed in saline solution at room temperature during the entire test course.

SEM Evaluation of Samples

Polyvinylsiloxane impressions (President light body, Coltene; Alstätten, Switzerland) of the core, including all margins with root dentin, were made prior to starting the experiment and also after each experimental phase (250,000, 500,000 and 1,000,000 cycles). The replicas were used for a semi-quantitative analysis of the external adhesive interfaces using scanning electron microscopy (Phillips XL 20; Eindhoven, NL), performed at a standard 250X magnification. Two evaluation parameters were considered: "continuity" or "marginal opening" (MO) to characterize each interface portion. The percentage defective interface (marginal opening) relative to the overall interface circumference was then calculated.

Upon completion of the 3 mechanical loading phases, samples were sectioned mesiodistally using a slow-rotation saw (Isomet 11-1180, Buehler; Evanston, IL, USA). The section surfaces were polished with 500- and 1200-grit silicon carbide paper (LaboPol-II, Struers; Willich, Germany) and acid etched for 10 s with a 32% phosphoric acid gel (Ultra-etch) for removing the smear layer. After thorough rinsing and careful blot drying, polyvinylsiloxane impressions were performed to fabricate new replicas for SEM semi-quantitative analysis of the internal adhesive interfaces, using the

same evaluation parameters. The different interfaces evaluated were:

- core-dentin
- composite cement-dentin
- composite-dentin (corresponding to the evaluation of the total restoration interface with dentin)
- composite cement-post

For the micromorphological evaluation of the interface, higher magnifications (up to 1000X) were used.

Confocal Microscopy Evaluation of Samples

Six additional Composipost samples were fabricated following the aforementioned restorative and adhesive procedures, the primer and bonding resin being respectively labeled with Fluorescein sodium (Merck; Darmstadt, Germany) and Rhodamine B (Fluka Chemie; Buchs, Switzerland). These samples were not submitted to mechanical loading. Among the 6 samples, 3 were sectioned buccolingually (single cut central to the sample) and the other 3 horizontally (sections were made every 1.5 mm, starting 1 mm below the core base) with a slowly rotating saw (Isomet 11-1180). One section side was polished with silicone carbide paper of decreasing grit sizes (500, 1200, 2400, and 4000 on a LaboPol-II device) and replicated for SEM evaluation in order to compare findings from SEM and confocal laser microscopy (CLSM) (Krypton-Argon laser MRC 1024, Biorad; Hercules, CA, USA). The replicas of vertical and horizontal sections were first observed with the SEM to identify locations with perfect adaptation and areas of debonding between the luting composite and radicular dentin. Then, real samples were observed with CLSM in an attempt to characterize the micromorphology of intact and failed interfaces.^{36,37,55}

Statistical Analysis

Results are expressed as the percentages of defective adaptation along composite core-dentin, composite cement-dentin, and composite cement-post interfaces (internal adaptation) or relative to the whole composite-dentin interface circumference (marginal adaptation). Nonparametric statistical analyses were performed for interface integrity. Differences between groups at each experimental phase were evaluated with the Kruskal-Wallis and Nemenyi tests; differences resulting from successive fatigue steps were analyzed with the Friedman and Wilcoxon-Wilcoxon tests (marginal adaptation only).

RESULTS

Marginal Adaptation

Results of the marginal adaptation evaluation are presented in Fig 2a and Table 2a. Percentages of marginal opening increased in all groups as the number of mechanical loading cycles and the loading force increased. The final proportion of marginal opening remained, however, below 20% in all groups. After 250,000 and 500,000 loading cycles, samples with zirconium oxide and stainless steel posts presented higher percentages of marginal opening compared to hybrid posts containing both carbon and quartz fibers. At the end of the loading test (1,000,000 cycles), samples with low-rigidity full quartz-fiber posts and high-rigidity stainless steel posts exhibited the highest proportion of gaps, while carbon fiber posts provided the best adaptation.

Internal Adaptation

Results of the internal adaptation evaluation are presented in Fig 2b and Table 2b. Significant differences between groups were detected for the interfaces between post and composite cement and between composite core and dentin. Despite few statistical differences, the overall variation in debonding proportions at the dentin/core interface was lower for anisotropic fiber posts compared to isotropic metal and ceramic posts. In contrast, comparable proportions of debonding were found at the composite cement/dentin interface. The whole dentin/composite interface showed percentages of debonding comparable to the composite cement/dentin interface, due to the limited contribution of the small coronal dentin surface to this calculation. The highest overall percentage of interfacial defects with dentin was found for the stainless steel posts.

Significant proportions of gaps were observed at the post/composite cement interface for isotropic metal and ceramic posts only (Table 2b). Regarding this interface, the highest proportions of gaps were found around smooth zirconium posts.

Micromorphology

The observation of intact continuous interfaces showed a clearly organized hybrid layer with a dense resin tag network, as demonstrated by dual fluorescence in both structures (Fig 3). Conversely, defective interfaces were usually characterized by incomplete hybrid layer and resin tag formation, with

limited or no bonding resin penetration within the demineralized dentin layer and tubules (limited or no rhodamine fluorescence in these structures) (Fig 4).

DISCUSSION

Materials and Methods

In order to limit variables inherent to a human origin of dental specimens⁷ and the restricted availability of human teeth, bovine deciduous teeth were used in this study to provide a more uniform root anatomy and standardized sample length. Since studies have reported little difference between human and bovine dentin as a bonding substrate,^{42,47} the use of bovine teeth seems advantageous to develop a standardized protocol for the evaluation of adhesive posts and cores.

Due to the absence of consensus on the restoration of endodontically treated teeth, numerous post materials and designs are available. With the aim of evaluating the influence of post physical properties on the post and core adaptation, posts of identical design but made with dissimilar raw materials were used in this study. Experimental posts made of titanium; stainless steel, and zirconium were therefore fabricated by the same manufacturer as commercially available fiber posts.

The force was applied to the samples at a 45-degree angle to the tooth's long axis, in accordance with most of published reports about post and core fracture and fatigue testing of anterior teeth.^{11,24,26} The artificial chewing cycle (duration, force profile, and frequency) was also designed to correspond as closely as possible to physiological conditions.^{1,4,17,41,43} As adhesive posts and cores are potentially indicated for restoring canines, a 100-N loading force was applied to the samples during the third experimental phase. In a similar *in vitro* fatigue trial, 1,200,000 loading cycles were estimated to simulate about 5 years of clinical function.²⁹

The presence of prosthetic restorations, especially those providing a ferrule effect, limits or negates the influence of post and core restoration on the mechanical resistance of endodontically treated teeth.^{2,15,22} Therefore, it was decided to apply the force directly to the core; even if it does not mimic a real clinical situation, this was considered necessary to emphasize the influence of post physical characteristics on restoration adaptation. In fact, this configuration corresponds to a restoration without ferrule effect, which is the less favorable biomechanical and clinical situation.^{3,18,22,31,52,53}

Confocal microscopy was used as an additional observation method because it allows the primer and bonding resin to be individually labeled and therefore eventual failures to be localized in relation to the different adhesive interface components.^{54,55} An additional advantage of confocal microscopy is to allow sub-surface observations, which enhance information significance.^{54,55} However, as fluorescent dyes are not stable in a wet environment, it was not considered appropriate for evaluating samples after the fatigue test and thus required the fabrication of additional restorations.

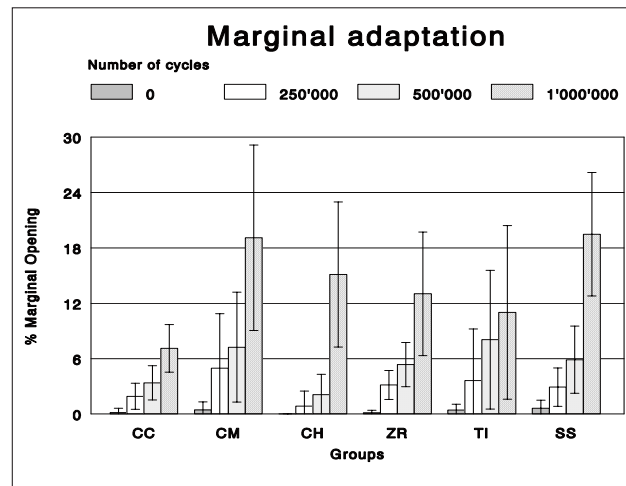


Fig 2a Percentages of marginal gaps, following the different mechanical loading phases (\pm SD).

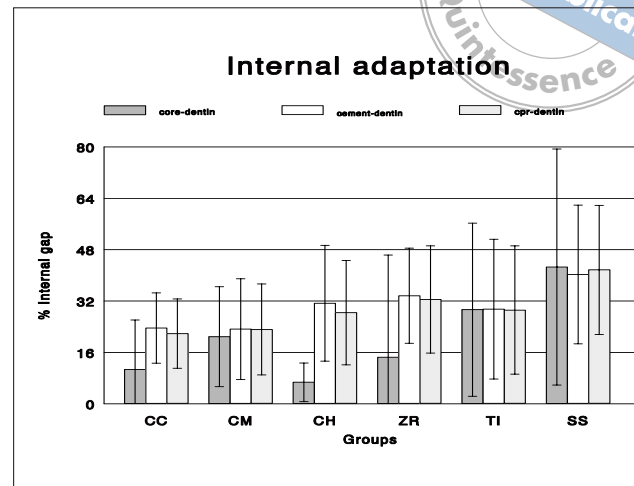


Fig 2b Percentages of internal gaps at dentin level, after mechanical loading (\pm SD).

Table 2a Mean, standard deviation of percentages of gaps at the marginal interface following the different mechanical loading phases

Number of cycles/ force (N)	Composipost (CC)	Aestheti-Plus (CM)	Aesthetipost (CH)	Zirconium post (ZR)	Titanium (TI)	Stainless steel post (SS)
0	0.2 \pm 0.46 ^{A,B}	0.4 \pm 0.86 ^C	0.01 \pm 0.03 ^{a,E}	1.5 \pm 1.09 ^{a,G,F}	0.4 \pm 0.65 ^{I,J}	0.9 \pm 0.87 ^{LM}
250,000/50	1.9 \pm 1.41	5.0 \pm 5.91 ^D	0.85 \pm 1.64 ^{b,c,F}	4.2 \pm 1.74 ^{b,H}	3.6 \pm 5.60 ^K	4.7 \pm 3.38 ^{c,N}
500,000/75	3.4 \pm 1.86 ^A	7.2 \pm 5.95	2.1 \pm 2.2 ^{d,e}	9.5 \pm 2.99 ^{d,G}	8.05 \pm 7.52 ^I	9.7 \pm 4.61 ^{e,L}
1,000,000/100	7.1 \pm 2.58 ^{e,f, B}	19.1 \pm 10.05 ^{e,CD}	15.1 \pm 7.86 ^{E,F}	16.5 \pm 5.89 ^{F,H}	11 \pm 9.41 ^{J,K}	17.4 \pm 3.34 ^{f,M,N}

Groups in rows with same superscript lower case letter are statistically different (Kruskal-Wallis and Nemenyi, $p < 0.05$); groups in columns with same superscript capital letter are statistically different (Friedmann and Wilcoxon-Wilcoxon, $p < 0.05$).

Table 2b Means and standard deviations of percentages of gaps at the internal interface after mechanical loading

Interface	Composipost (CC)	Aestheti-Plus (CM)	Aesthetipost (CH)	Zirconium post (ZR)	Titanium (TI)	Stainless steel post (SS)
Composite core-dentin	10.57% \pm 15.44	20.79% \pm 15.55	6.59% ^a \pm 5.99	33.75% \pm 31.92	29.19% \pm 24.98	37.68% ^a \pm 29.21
Composite cement-dentin	23.44% \pm 10.95	23.11% \pm 15.69	31.17% \pm 18.02	21.33% \pm 15.19	29.31% \pm 20.13	47.47% \pm 21.78
Composite-dentin (total interface)	21.69% \pm 10.81	22.99% \pm 14.15	28.2% \pm 16.25	21.98% \pm 15.88	29.02% \pm 18.49	47.37% \pm 20.33
Composite cement-post	0% ^b	0% ^c	0% ^d	22.61% ^{b,c,d} \pm 13.65	10.27% \pm 10.89	14.80% \pm 13.06

Groups with same superscript letter are statistically different (Kruskal-Wallis and Nemenyi, $p < 0.05$).

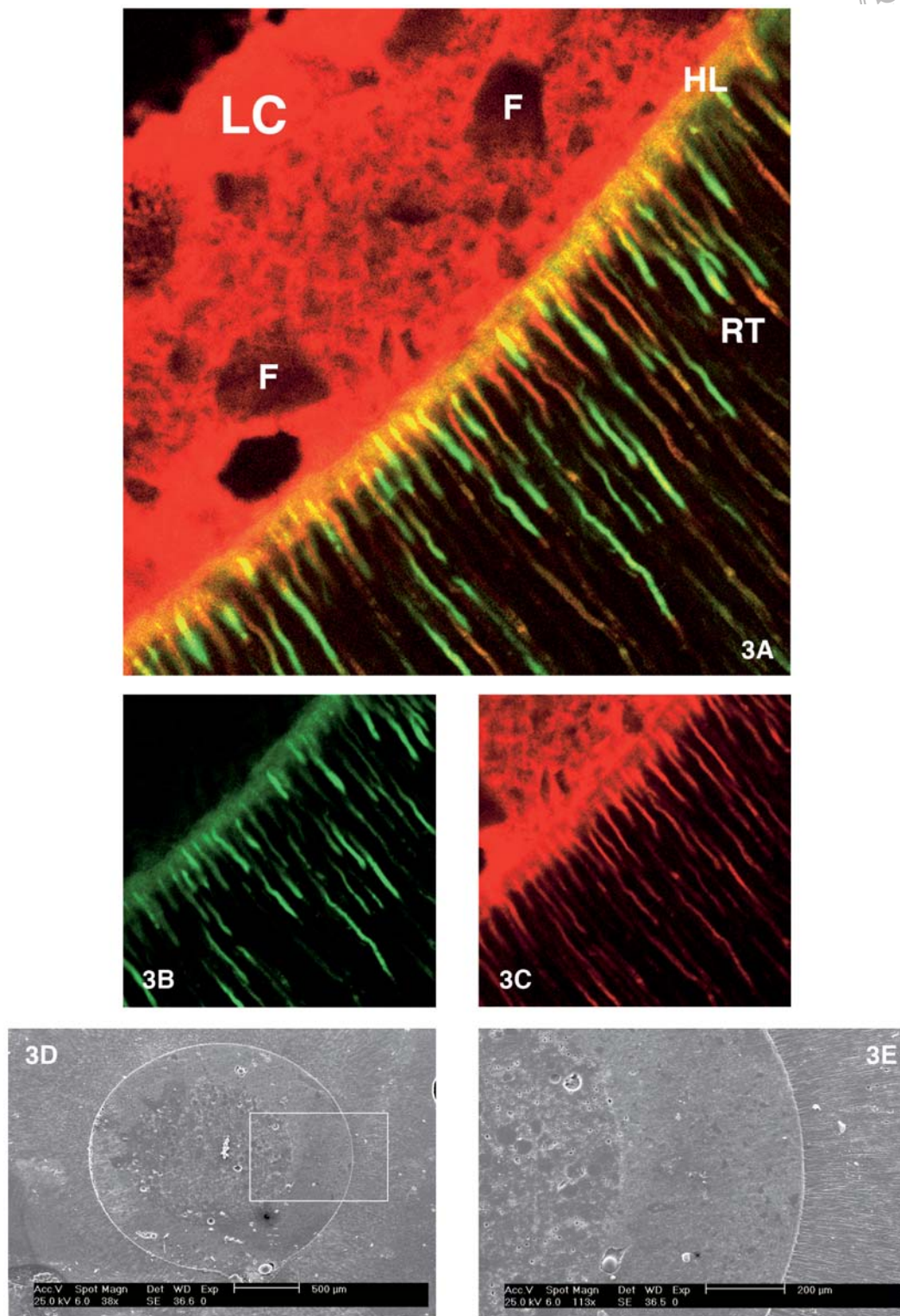


Fig 3a Confocal and SEM microphotographs depicting the morphological characteristics of a perfect adhesive interface. The hybrid layer (HL) shows a marked dual fluorescence and a dense resin tag network (RT) visible at the tubule entrance. The luting cement layer (LC) can be seen in the left upper corner; the filler particles are clearly visible (F).

Figs 3b and 3c Magnified views of figure A; Fig 3b and 3c respectively show the distribution and penetration of the primer (labeled with fluorescein) and bonding resin (labeled with rhodamine B) (60X lens, oil immersion, 1.4 numerical aperture).

Figs 3d and 3e Views of the same samples under SEM, which confirm that the interface is free of any defect (original magnification 28X [d] and 113X [e]).

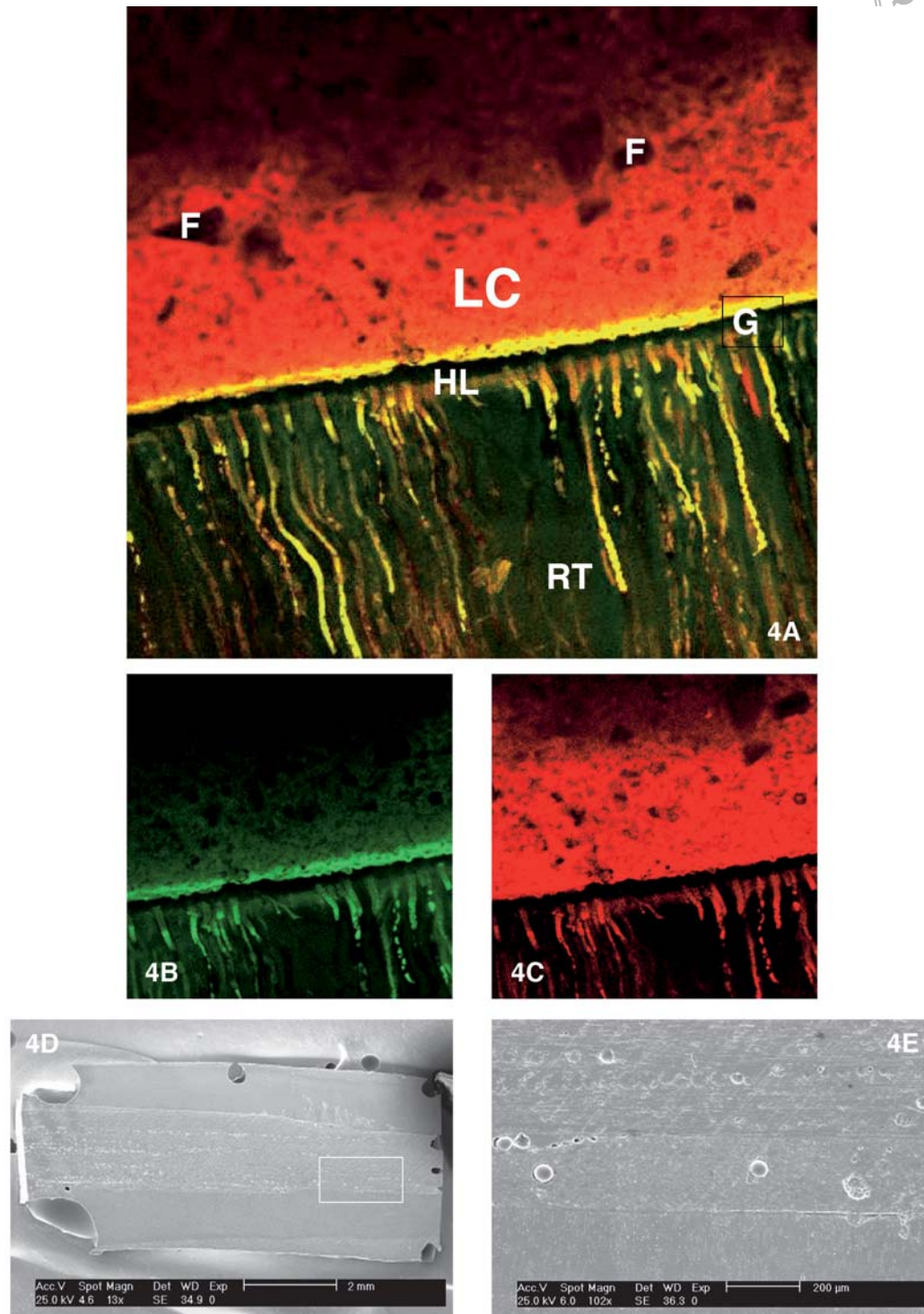


Fig 4a Confocal and SEM microphotographs depicting the morphological characteristics of a failed adhesive interface. There is less fluorescence induced by the rhodamine B in the hybrid zone or tubule entrance, and the gap (G) seems located above the hybrid layer (HL). The luting cement layer (LC) with filler particles can be seen on the upper side.

Figs 4b and 4c Magnified views of Fig 4a; figs 4b and 4c respectively show the distribution and penetration of the primer (labeled with fluorescein) and bonding resin (labeled with rhodamine). Note the reduced rhodamine fluorescence in the hybrid zone and tubules, demonstrating a reduced bonding resin penetration and resin tag formation (RT) in dematerialized dentin (60X lens, oil immersion, 1.4 numerical aperture).

Figs 4d and 4e Views of the same samples under SEM, which confirm the presence of a gap in this area (original magnification 13X [e] and 203X [f]).

Marginal Adaptation

As expected, only nonsignificant differences were observed before sample loading; marginal opening percentages were also extremely low, showing that the selected configuration was compatible with a composite core realized by the direct technique. In fact, due to the favorable ratio between bonded and free surfaces (C-factor),¹² composite polymerization shrinkage proved not to adversely affect initial core marginal adaptation. However, the incidence of debonding at the tooth-restoration margins increased in all groups due to mechanical loading. This increase was more important with the most and least rigid materials. Despite "severe" test conditions, the overall post-loading percentages of "marginal opening" remained relatively low, with only a few significant differences. This also reflects the efficacy of selected adhesive materials.

Composite cores with carbon fiber posts proved to be the most resistant to mechanical loading. During the second and third experiment phases, an increase in marginal opening was observed for the least rigid posts (pure quartz and hybrid quartz-carbon fibers); this probably reflects an increased sample deformation which negatively affected coronal adaptation. Insufficient rigidity is not only potentially detrimental to the post-core adaptation but also to the fracture resistance of prosthetic restorations, especially all-ceramic ones.⁴⁸ With the more rigid posts (groups SS, ZR, TI), proportions of marginal opening were found to be lower than expected; this could be explained by a relatively stable cohesion between the different restoration elements (limited interfacial debonding), at least until 1 million cycles. Finite element analysis has actually shown that increased post stiffness reduces sample deformation in the cervical area^{21,45,57} but increases stresses in the lower root portion.⁴⁴ Due to the cylindrical shape of the root canal in deciduous bovine teeth, the narrow post tip was mostly embedded in luting composite. One can hypothesize that the thicker luting cement layer existing in these areas acted as a stress absorber-stress breaker,^{7,48} and helped temper the expected influence of post physical properties. In order to establish a better correlation between in vitro and clinical conditions, and to reveal differences in the post and core behavior, an increase in loading cycle number appears necessary for further studies.

The fatigue behavior of the different fiber posts used in this study has also been evaluated after crown placement and under forces of higher magnitude, up to 250 N.^{26,35} Failure rates and fracture severity were significantly higher in teeth restored with metallic and ceramic posts, demonstrating a clear advantage of posts with physical properties close to those of natural tissues. However, forces applied in these in vitro trials were close to average maximal biting forces at occlusion,^{32,33} which likely corresponds to para-functional stresses rather than normal masticatory strains.

In the current experimental setup, the post head was exposed to a saline bath (inside fatigue chambers), because no crowns were placed. The literature shows that a possible degradation of fiber posts in an aqueous environment is a controversial matter.^{36,51} Although the present restoration configuration is not clinically relevant, the overall satisfactory behavior of fiber-post restorations did not confirm this

potential degradation risk, at least given a short exposure time.

Internal Adaptation

Although it was significant only for the difference between stainless steel and hybrid carbon-quartz posts, the trend was that the gap incidence at the core/dentin interface was higher with the more rigid ceramic and metal posts. The same behavior was observed with stainless steel vs mineral and carbon posts in terms of the luting cement/dentin interface. With very few exceptions, the proportion of adhesive failures was higher at each interface with rigid isotropic posts compared to anisotropic posts. These findings confirm marginal adaptation results and the aforementioned differences in the behavior between isotropic metal-ceramic and softer anisotropic fiber posts.

The anisotropy of the fiber posts was described as a clear advantage over metal or ceramic posts, the properties of which seem poorly compatible with tooth biomechanics^{9,10} and dentin micromorphology.^{39,56} The results of the present study do not, however, make it possible to ascertain the respective influence and advantage of fiber post anisotropy and reduced elasticity modulus.

The present results are in accordance with previous studies.^{7,26,35} In one study applying the same protocol but using human teeth,⁷ fewer marginal and internal defects were found for cores made with fiber vs metal or ceramic posts; however, the posts under evaluation had different designs.

Increasing the loading force within the limits of human physiological function might represent another approach to reveal differences in post and core behavior, although an increase of loading cycles appears to be a more appropriate means of simulating long-term clinical performance.

Micromorphology of the Dentin/Luting Cement Interface

Confocal microscopy was used in a few other studies for evaluating the adaptation of fiber posts to radicular dentin,^{7,35} but did not lead to conclusive observations. Conversely, the present study presented clear micromorphological descriptions of interfaces with perfect or incomplete hybrid layer and resin tag formation in relation to good or defective cohesion between dentin and luting materials. The presence of areas with incomplete adhesive interface formation might be attributed to limited access for application instruments and adhesive components inside the canal or an improper manipulation of the adhesive system, such as incomplete canal cleaning and drying or insufficient removal of primer solvent excesses.

CONCLUSION

Within the conditions of the present study, the following conclusions may be drawn:

- The study hypothesis that post physical properties influence internal adhesive post and core adaptation after mechanical loading was confirmed.

- Considering the performance of selected adhesive procedures, resin-fiber posts appeared more favorable for restoration adaptation than more rigid posts, especially those made of stainless steel. It can be hypothesized that better adhesion between the resin-fiber posts and resin composite and a better match between restorative materials and dentin physical properties are responsible for this finding.
- Esthetic white resin fiber posts which exhibit a lower elasticity modulus did not perform as well as those containing only carbon fibers.
- Although there was no ferrule effect or protective prosthetic structure, internal adaptation of adhesive post and cores in the worst case (stainless steel posts) remained below 50% of internal debonding after the loading test.
- Confocal microscopy revealed a well-organized hybrid layer and resin tag formation wherever a cohesive interface with dentin was present. In the presence of a gap, however, limited or no penetration of bonding resin into demineralized dentin and tubules was observed.

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Clinical relevance: Considering existing adhesive performance, the use of semi-rigid fiber-reinforced posts, such as carbons posts, is recommended for large preprosthetic coronal buildup rather than rigid ceramic or softer white fiber posts.