Effect of Different Cements on the Biomechanical Behavior of Teeth Restored with Cast Dowel-and-Cores—In Vitro and FEA Analysis

Carlos José Soares, DDS, MS, PhD,[1] Luís Henrique Araújo Raposo, DDS,[1]
Paulo Vinícius Soares, DDS, MS, PhD,[1] Paulo César Freitas Santos-Filho, DDS, MS, PhD,[1]
Murilo Sousa Menezes, DDS, MS, PhD,[1] Priscilla Barbosa Ferreira Soares, DDS, MS,[2]
& Denildo Magalhães, DDS, MS, PhD[2]

[1] Biomechanics Group, Department of Operative Dentistry and Biomaterials, School of Dentistry—Federal University of Uberlandia, Uberlândia, Brazil
[2] Biomechanics Group, Department of Periodontology and Implantology, School of Dentistry—Federal University of Uberlandia, Uberlândia, Brazil

Keywords
Cast dowel-and-core; finite elements analysis; fixation cement materials; fracture resistance.

Correspondence
Carlos José Soares, Federal University of Uberlandia – Operative Dentistry and Dental Materials, Av. Pará 1720, 2B, sala 2B24 Uberlandia, Minas Gerais 38400-902, Brazil.
E-mail: carlosjsoares@umuarama.ufu.br

Supported by grant No. APQ3928 from the Research Support Foundation of the State of Minas Gerais (FAPEMIG).

Accepted: December 29, 2008

doi: 10.1111/j.1532-849X.2009.00527.x

Abstract

Purpose: To test the hypothesis that the type of cement used for fixation of cast dowel-and-cores might influence fracture resistance, fracture mode, and stress distribution of single-rooted teeth restored with this class of metallic dowels.
Materials and Methods: The coronal portion was removed from 40 bovine incisors, leaving a 15 mm root. After endodontic treatment and standardized root canal relief at 10 mm, specimens were embedded in polystyrene resin, and the periodontal ligament was simulated with polyether impression material. The specimens were randomly divided into four groups ($n = 10$), and restored with Cu–Al cast dowel-and-cores cemented with one of four options: conventional glass ionomer cement (GI); resin-modified glass ionomer cement (GR); dual-cure resin cement (RC); or zinc-phosphate cement (ZP). Sequentially, fracture resistance of the specimens was tested with a tangential load at a 135° angle with a 0.5 mm/min crosshead speed. Data were analyzed using one-way analysis of variance (ANOVA) and the Fisher test. Two-dimensional finite element analysis (2D-FEA) was then performed with representative models of each group simulating a 100 μm cement layer. Results were analyzed based on von Mises stress distribution criteria.
Results: The mean fracture resistance values were (in N): RC, 838.2 ± 135.9; GI, 772.4 ± 169.8; GR, 613.4 ± 157.5; ZP, 643.6 ± 106.7. FEA revealed that RC and GR presented lower stress values than ZP and GI. The higher stress concentration was coincident with more catastrophic failures, and consequently, with lower fracture resistance values.
Conclusions: The type of cement influenced fracture resistance, failure mode, and stress distribution on teeth restored with cast dowel-and-cores.

Intraradicular retention is commonly used in endodontically treated teeth that have suffered excessive coronary structure loss.[1] The insertion of a dowel inside the root canal is a viable alternative to increase retention and provide stability for the final restoration.[2,3] Cast dowel-and-cores are still the standard alternative used by clinicians.[4] Although this approach requires more time, is costly, and is not as esthetic as fiberglass dowels, some studies point to high success rates when this type of retention apparatus is used.[5,6] Moreover, these systems present advantages in certain clinical situations, as when multiple teeth require dowels, when an extensive prosthesis with intraradicular retention is used, or even when the coronary structure is completely absent; however, some authors have observed that dowels may influence the mechanical resistance of teeth, increasing the risk of damage to residual tooth structure.[7-11] Additionally, the amount of coronal and root dentine that remains after a root canal therapy and dowel space preparation also plays an important role in the longevity of the restoration and consequently the tooth.[12,13]

The retention of cast dowel-and-cores into the radicular structure is highly influenced by length, diameter, shape,[14,15] and type of cement.[16] An ample assortment of cements are available to clinicians and have been continuously evaluated in the application of intraradicular retainers.[17] Studies have demonstrated conflicting retention results for various types of cement.[18-21] Cements such as glass ionomer, resin-modified glass ionomer, zinc-phosphate, and dual-cure resin cement have commonly been used for the fixation of dowel-and-cores, with acceptable clinical results, although not all researchers agree. The capability of a cement to retain dowels is directly related to its mechanical properties and the level of adhesion to dentin and metal alloys,[22] beyond the stability of the intraradicular retainer into the root canal.[23]

The interaction among cast dowel-and-core, cement, and root dentin may result in biomechanical changes due to differences in the properties of the components. Alloys and cements present differing stiffness and elastic moduli, which are decisive in defining the biomimetic behavior of the whole complex, considering that the capability of a structure to resist loads without harmful distortions is directly related to this factor.[24] The difference in elastic modulus among dentin, intraradicular retainers, and cements could result in stress concentration at the restoration interface when the tooth is in function.

During biomechanical analysis of dental structure and restorative materials, destructive mechanical tests such as fracture resistance rehearsals are important methods for analyzing tooth behavior in situations of high load application;[25-27] however, there are limitations related to obtaining data from the whole behavior of the tooth-restoration complex. The use of non-destructive methodologies, such as finite element analysis (FEA), seem to be an appropriate method for obtaining answers about the interferences caused by the restorative process in the complete structure. Laboratory tests and FEA together contribute to a more comprehensive mechanical behavior analysis.[28-30]

Furthermore, in the mechanical analysis of teeth restored with new prefabricated fiber dowels, cast dowel-and-cores are commonly used as controls for comparisons with these systems;[31,32] however, in some studies, the cementation protocol is divergent because of differences in the fixation agents used, such as resin cements to fiber dowels and zinc-phosphate cement to cast dowel-and-cores.[33,34] The non-standardization of these variables during tests may influence the final results, masking the analysis of real factors in the study.

Most cements have approximately the same modulus range and would be expected to perform about the same way, except for differences in bonding to tooth structure or cast materials, which might affect interfacial stresses. In this context, this study aimed to test the hypothesis that the type of cement used for fixation of cast dowel-and-cores might influence fracture resistance, fracture mode, and stress distribution of single-rooted teeth restored with this class of metallic dowels.

Materials and methods

Forty bovine incisors with similar dimensions were selected and stored in 0.2% thymol solution.[35] All external debris was removed with a hand scaler, and the anatomic crowns of all teeth were sectioned horizontally to the long axis up to 15 mm to the apical limit, with the use of a water-cooled diamond disk (KG Sorensen, Baurueri, Brazil). Specimens were then stored in saline solution at 37°C for the same time until the tests.

Root canals were instrumented with a K-50 master apical file (Dentsply Maillefer, Ballaigues, Switzerland), in association with the chemical action of 1% sodium hypochlorite (NaOCl, Cloro Rio 1%, São José do Rio Preto, Brazil), and filled with gutta-percha (Dentsply Maillefer, Petrópolis, Brazil) and endodontic sealer (Sealer 26, Dentsply Maillefer, Petrópolis, Brazil). Root canal relief was performed initially with a heated instrument (GP heater, Dentsply Maillefer, Ballaigues, Switzerland), and the residual gutta-percha was then removed with Gattes-Gliden burs (Dentsply Maillefer, Ballaigues, Switzerland), standardizing the relief at 10 mm and preserving 5 mm of gutta-percha in the apex. After this, the root canal walls were enlarged with a 5 bur (Largo Peeso Reamer, Dentsply Maillefer, Ballaigues, Switzerland), 1.5 mm in diameter, mounted on a low-speed hand-piece (KaVo do Brasil, Joinville, Brazil).

The specimens were inspected for cracks at 6× magnification (Leica, Hanau, Germany), and specimens presenting any cracks were discarded. To reproduce tooth movement inside the alveolus, the periodontal ligament was simulated with a 0.3-mm-thick layer of a polyether impression material (Impregum F, 3M ESPE, St Paul, MN).[27,36] The roots were axially embedded in a polystyrene resin (AeroJet, Santo Amaro, Brazil) up to 2 mm below the crown, simulating bone support. Following this, the specimens were randomly divided into four groups ($n = 10$) and restored with Cu–Al cast dowel-and-cores cemented with: GI, conventional glass ionomer cement (Ketac CEM, 3M ESPE, Seefeld, Germany); GR, resin-modified glass ionomer cement (RelyX luting cement 3M ESPE, St Paul, MN); RC, dual-cure resin cement (RelyX ARC, 3M ESPE, St Paul, MN); ZP, zinc-phosphate cement (ZCI Zinc cement, SS White, Rio de Janeiro, Brazil). The materials and their composition are described in Table 1. The cast dowel-and-core patterns were made from autopolymerizing acrylic resin (Duralay, Reliance Dental Mfg. Co, Worth, IL), replacing the coronal portion with a 6-mm high core. Acrylic patterns were then invested and cast with a Cu–Al alloy (Duracast, São Paulo, Brazil).

Root canals were rinsed with 0.12% chlorexidine and dried with air spray and paper points. For dual-cure resin cement specimens, the root canal walls were etched with 35% phosphoric acid gel (Scotchbond etchant, 3M ESPE, St Paul, MN) for 15 seconds, rinsed with air–water spray for another 15 seconds, and dried with absorbent paper points (Dentsply Maillefer, Petropolis, Brazil). The adhesive system (Adper Scotchbond Multipurpose, 3M ESPE, St Paul, MN) was applied as follows: application of two coats of primer followed by a 20-second pause for air drying and application of one adhesive coat followed by another 20-second pause; excess solution was removed from the canal using a microbrush, then light-curing was performed for 20 seconds.[37] RelyX ARC was mixed according to the manufacturer's instructions and inserted into the root canal with a lentulo drill (Dentsply Maillefer, Ballaigues, Switzerland). After this, the dowel was seated in position, and the excess cement was removed. Light-curing was performed for 40 second with a halogen light unit (XL-3000, 3M ESPE, St Paul, MN) at 850 mW/cm^2. For the other cements, no treatments were performed in the root dentin. Resin-modified glass ionomer, conventional glass ionomer, and zinc-phosphate cements were manipulated according to manufacturer's instructions and inserted into the root canal with a lentulo drill. Dowels were then positioned, and excess material was removed. All cemented dowels were submitted to 5-minute 500 g pressure at the tooth's long axis.

Table 1 Cements: manufacturers and composition

Material	Name	Manufacturer	Composition	Lot number
Conventional glass ionomer cement (GI)	Ketac Cem	3M ESPE, Seefeld, Germany	Powder: Glass powder, polycarboxylic acid, pigment Liquid: water, tartaric acid, conservation agents[a]	313320
Resin-modified glass ionomer cement (GR)	RelyX Luting	3M ESPE, St Paul, MN	Powder: fluoroaluminosilicate glass, potassium persulfate, ascorbic acid, opacifying agent[b] Liquid: methacrylated polycarboxylic acid, water, HEMA, tartaric acid[b]	20000821
Dual-cure resin cement (RC)	RelyX ARC	3M ESPE, St Paul, MN	Paste A: BisGMA, TEGDMA, zirconia/silica filler, pigments, amine, photoinitiators[c] Paste B: BisGMA, TEGDMA, zirconia/silica filler, benzoyl peroxide	FKGW
Zinc-phosphate cement (ZP)	ZCI Zinc cement	SS White, Rio de Janeiro, Brazil	Powder: zinc oxide, magnesium oxide, colorant CI 77288[d] Liquid: orthophosphoric acid, aluminum hydroxide, zinc oxide, distilled water[d]	Powder: 0881207 Liquid: 0061207

[a]3M ESPE Ketac Cem Glass Ionomer Cement technical product profile—p. 10.
[b]3M ESPE RelyX Luting Cement technical product profile—p. 9;
[c]3M ESPE RelyX ARC Adhesive Resin Cement technical product profile—p. 10
[d]SS White ZCI Zinc Cement technical product profile—p. 1.

After this, specimens were mounted on a metallic device positioned in a mechanical testing machine (EMIC DL-2000, São José dos Pinhais, Brazil). The load was applied at a 135° angle to the long axis using a 2-mm-diameter steel sphere. The load application point was the center of the lingual surface (Fig 1). Specimens were tested at a 0.5 mm/min crosshead speed until fracture. Fracture resistance was then recorded (N), and the failure mode of each root was observed under a stereoscopic magnification device (Leica). The failures were classified into three types: I—cast dowel-and-core removal, II—coronal third fractures, and III—medium third fracture.[38] Fracture resistance data were analyzed using a one-way analysis of variance (ANOVA) following the Fisher test ($p < 0.05$). Results of failure mode were analyzed with frequency distributions for each group.

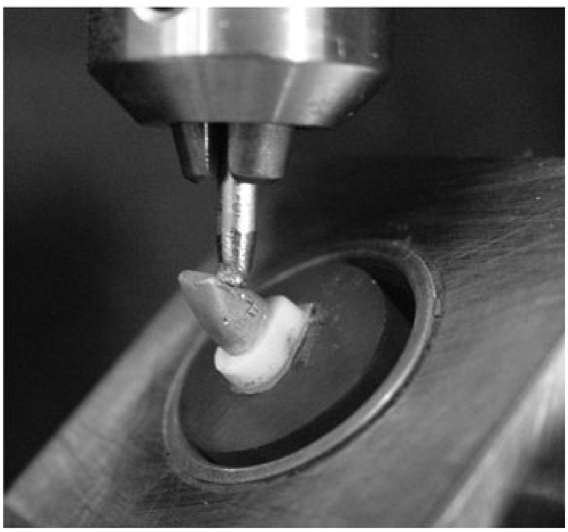

Figure 1 Application of load to the cast dowel-and-core assembly. Loading pin with a 3-mm rounded tip was contacted along the lingual surface of the core at a 135° angle to the long axis of the tooth. The dowel-and-core was cemented within an extracted tooth root, which had been coated with impression material to create a pseudo-periodontal ligament. The entire assembly was embedded into a cylindrical polystyrene resin base mounted in a metal holder on the loading equipment.

Representative 2D numerical models for each experimental group were created for 2D-FEA from a longitudinal cut of an incisor in the buccal–lingual plane. All structures of the complex were created using CAD software (Mechanical Desktop 6, Autodesk Inc., San Rafael, CA). The external outline of the tooth specimen, its position in the polystyrene resin base, and the simulated periodontal ligament were included in the model with the intention of reproducing the experimental conditions prevailing as a result of the fracture resistance test.[30] Data were exported to FEA software (Ansys 9.0, Ansys Inc., Houston, TX) in the IGES format. Areas corresponding to each structure were plotted, and then meshed with isoparametric elements of eight nodes (Plane183) in accordance with the mechanical properties of each structure and materials used in the test models (Table 2). The interfaces of the structures were assumed as perfect and continuous, with a 100-μm cement layer. All tooth structure and materials used in the models were considered isotropic, elastic, linear, and homogeneous. A tangential compressive static load of 30 N was applied at a 135° angle at the center of the concavity formed in the lingual face, simulating the fracture resistance test. The boundary conditions were specified to be consistent with physiological conditions, and the models were restricted at the lateral contour of the cylinder (Fig 2). Quantitative analyses using the von Mises stress distribution criteria were performed at 29 stress monitoring points into the cement line (Fig 3).

Table 2 Mechanical properties of dental structure and restorative materials: elastic modulus (*E*) and Poisson's ratio (ν)

Material	*E* (GPa)	Poisson's ratio
Dentin	18.6[44]	0.31[44]
Ligament	0.0689[44]	0.45[44]
Polystyrene resin	1.37[45]	0.30[45]
Gutta-percha	0.69[44]	0.45[44]
Zinc-phosphate cement (ZCI Zinc Cement)	22.4[44]	0.25[44]
Dual-cure resin cement (RelyX ARC)	7.0[46]	0.27[11]
Resin modified glass ionomer cement (RelyX luting)	4.0[46]	0.30[47]
Glass ionomer cement (Ketac Cem)	16.9[48]	0.30[47]
Copper-aluminum alloy	200.0*	0.30*

*Duracast Cu–Al dental alloy brochure.

Results

Fracture resistance means and standard deviations are detailed in Figure 5. One-way ANOVA showed significant differences among groups. The Fisher test demonstrated that the RC group showed fracture resistance values significantly higher than GR and ZP groups. The GI group presented fracture resistance values similar to the RC group and to the GR and ZP groups.

Failure mode results are illustrated in Figure 6. In the GR group, a reduced number of root fractures occurred despite a higher number of dowel-and-core removals. The RC and GI groups also presented a similar failure mode with the same reduced number of dowel-and-core removals, characterized by total or partial dislodgement of the metallic dowel. A high number of root fractures were observed in the ZP group with few dowel-and-core removals.

Two-dimensional FEA showed a variation in the stress concentration on inner dentin walls and into the cement line. Higher stress values were observed in models restored with ZP and GI. Teeth restored with dowels fixed with RC and GR demonstrated lower stress values in the completeness of the cement line (Fig 4). Although the four cements analyzed have different mechanical properties, the stress distribution along the dental structure was almost the same for all studied groups.

Discussion

The hypothesis tested was confirmed. Cement properties influenced not only fracture resistance and the failure mode of roots restored with cast dowel-and-cores, but also the stress distribution found.

High stiffness materials such as metal dowels significantly withstand deformation, generating high-stress concentrations at the interfaces.[39] In a system with complex stress distribution, as when a tooth has a stiff dowel cemented into its canal, this behavior could result in enhanced stress generation and accrual inside the more rigid body, inducing possible crack formation inside the root, which may culminate in a dental failure as a result of fatigue.[40] The difference between dentin elastic modulus and elasticity of dowel-and-core material may promote stress concentration in the adjacent dental structures.[41]

Although cast dowel-and-cores present a tendency to concentrate more stresses due high elastic modulus and consequent stiffness, many clinicians still use this technique as the first rehabilitative option, even when fiber dowels, though cemented in the same way, offer a more suitable option, favoring the stress distribution through the root and resulting in a more mechanically homogeneous system.[1,42] Moreover, a tooth restored with a fiber dowel presents a behavior more similar to the sound teeth than when a metallic dowel is used. On the other hand, metallic dowels present a large variation of the mechanical properties due to the type of metallic alloy employed. The high-stress concentration in the root portion of the metallic cast dowel-and-core is inevitable, a factor that is not reduced by changing the fixation cement type. This behavior explains the increased number of root fractures and the absence of core body fractures, as normally occurs when fiberglass dowels associated with composite resin are used.[43]

RC and GR cements presented a reduced elastic modulus and consequently more favorable mechanical behavior when compared to cements without polymer incorporation such as ZP and GI. In regions where the tooth is more heavily used such as in the vestibular wall (Fig 3—points 9 to 12), the apical region (Fig 3—point 14 region), and the palatine wall (Fig 3—point 17 region and points 18 to 21), the difference between the behavior of the polymeric and non-polymeric materials is clear.

Moreover, it was observed in this study that mechanical property variations of fixation cements directly influenced stress distribution patterns inside the cement line and the root canal internal walls. As seen, the higher the elastic modulus, the higher the cement stiffness, which can induce an enhanced stress concentration at the cement–dentin interface; however, when these alterations are associated with the failure mode obtained through fracture resistance tests, they seem to be less significant in the fracture process, because little difference is observed at the location where the fracture is most frequent (root cervical portion) when stress levels between the models are taken into account. This observation is supported by the failure mode that had not shown a direct correlation to the type of cement used.

The specimens cemented with RC displayed a higher fracture resistance than the specimens with retainers fixed with GR or ZP. This outcome can be explained by the bonding of the resin cement to dentin, produced by use of an adhesive system. RC allows better stress distribution to the root portion than the other cements, demonstrating lower stress accumulation at the resin cement line. Cast dowel-and-cores cemented with GR presented low fracture resistance values, probably as a result of the frequent occurrence of core displacement before the complete fracture of the specimens. This behavior seems to be related to the low retention capacity, probably caused by cohesive fractures or by a low adhesion to dentin.

The GI group showed similar fracture resistance values to the RC group, which can be explained by the bonding capacity of both materials to metal and dentin. The mechanical properties of this cement qualify it as an intermediate behavior material, between plastic and friable behaviors.

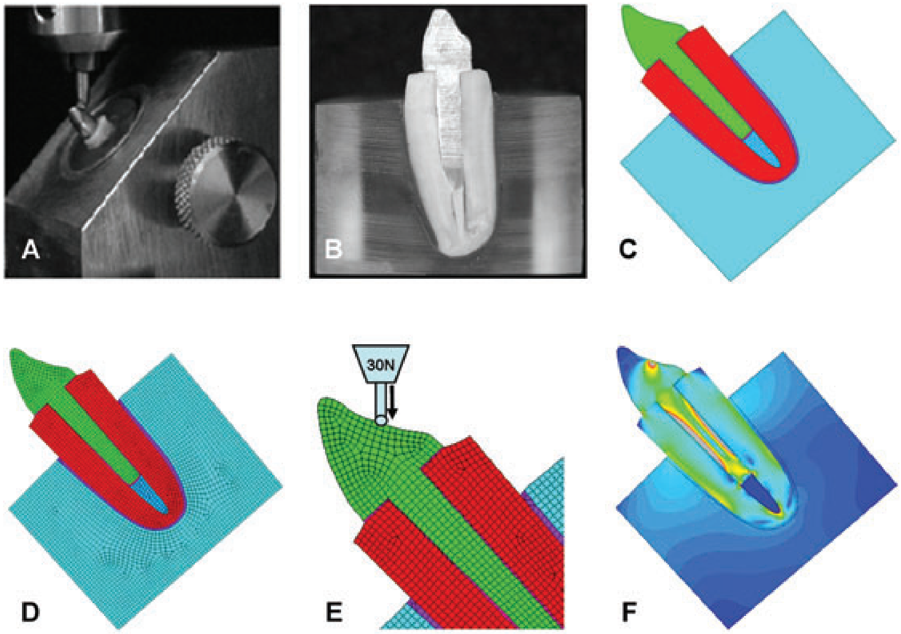

Figure 2 Example of 2D-FEA mimicking the laboratory tests: (A) laboratory test set-up; (B) longitudinal cut of the specimen; (C) 2D map of materials areas for FEA; (D) meshing for 2D-FEA; (E) magnified view of mesh and loading condition; (F) Example of 2D-FEA stress distribution during loading.

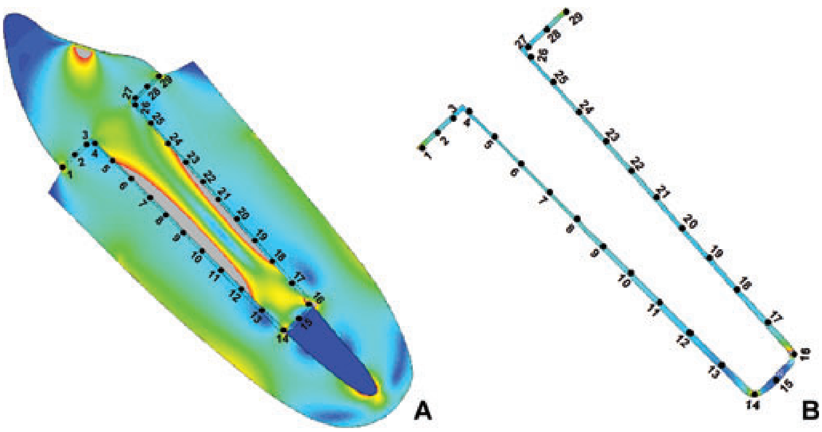

Figure 3 (A) Stress monitoring points in the dentine–cement–dowel complex; (B) stress monitoring points in the cement line.

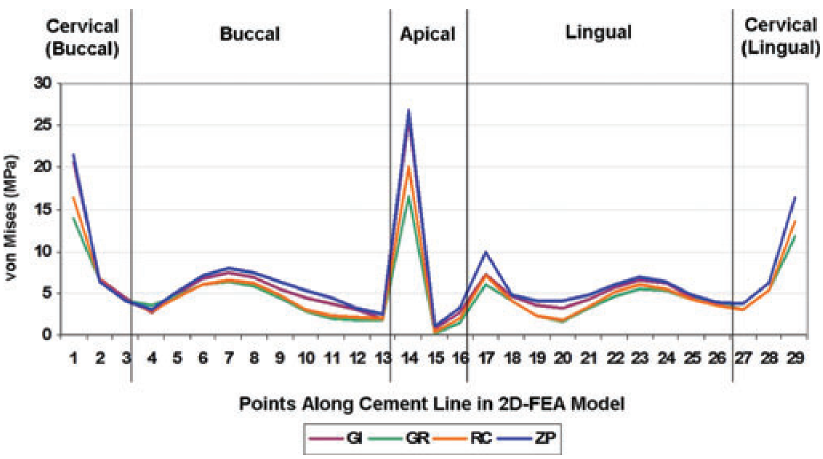

Figure 4 von Mises stress levels from 2D-FEA for the preselected points in Figure 3 at maximum loading for each cement type.

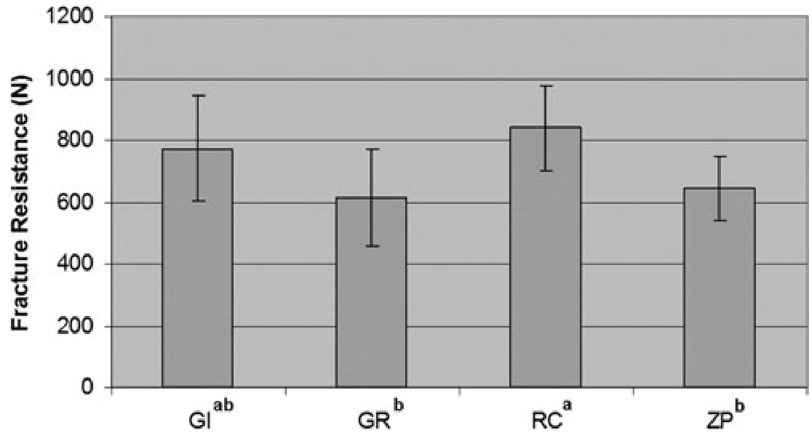

Figure 5 Fracture resistance (means and standard deviations) of cemented dowel-and-core assemblies for different cement types (Fisher's test demonstrated differences among cements as indicated by the letters superimposed on the cement abbreviations).

The higher stress values observed with the ZP cementation line correlate directly to the failure mode found in the same group, whereas 90% of the specimens presented fractures of the dental structure (Fig 6) and the fracture resistance values were significantly lower. In addition to the high elastic modulus (E), the low deformation capability and the brittle comportment of this material (Table 2), another important point that explains the behavior observed in the specimens of this group is the absence of bonding between the cementation agent and the dental tissue. Thus, the stress transmission to the dentin in this group was probably higher, reducing fracture resistance and, consequently, increasing the number of dental fractures.

Although lower fracture resistance results were presented by the specimens restored with cast dowel-and-cores cemented with ZP, this fixation agent can still be used as an alternative, because these resistance values are higher than the incident forces found clinically. In addition, subsequent studies analyzing the performance of roots restored with dowels should standardize the cementation techniques and materials used for all dowel types, even though cast dowels are used as controls, making the comparison of results easier and less discrepant.

A limiting aspect of this study is related to the monotonic static loading method, which may not represent an in vivo situation, where repetitive fatigue loading is characteristic.[44] The direct load application over the core may be another limitation that simulates the experimental condition but does not reproduce the real clinical situation; however, this was used as a way to emphasize the real influence of the cements' properties on the root canal/dowel interface, standardizing the specimens, thus excluding the effect of ferrules, crowns, and the interaction between the crown and the metallic core. Another limitation of the study was the use of 2D models, also with static load application, not taking into account the progressive behavior of the restorative materials during the loading process. Moreover, the models were not fully restored, and presented perfect and continuous interfaces, with a regular cement layer thickness, which is not a fact in clinical practice. The association of destructive mechanical tests (fracture resistance) and 2D-FEA (stress

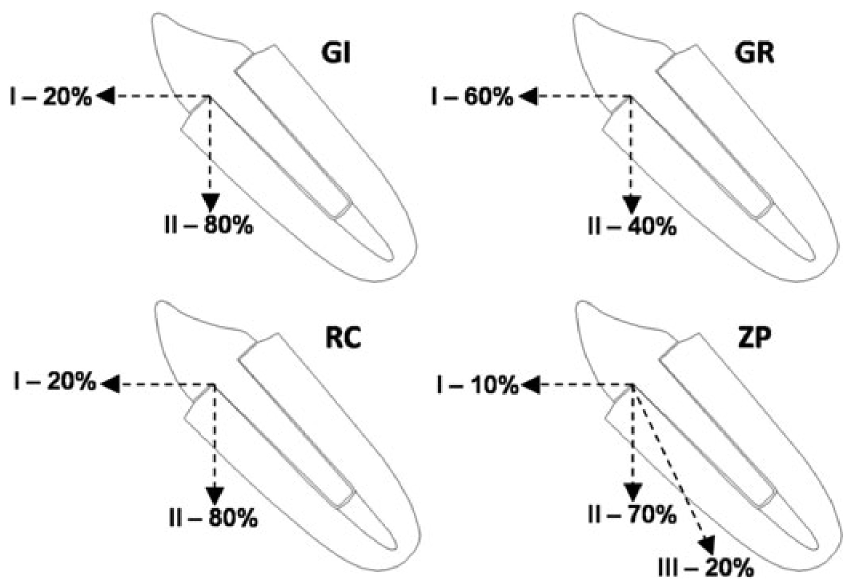

Figure 6 Fracture patterns for laboratory tests involving different cement types. For each cement, the fracture types of paths (I, II, III) for the ten specimens are indicated by the dotted lines and labels in the figure.

distribution) proved to be an efficient tool in the analysis of complex structures. Furthermore, FEA using 3D models is recommended, as it allows anatomic alterations and device/specimen contact to be shown with greater fidelity.

Conclusions

Within the limitations of this in vitro study, the following conclusions can be drawn:

(1) The cement type influenced the stress pattern, fracture resistance values, and failure distribution among the groups.
(2) Zinc–phosphate cement and conventional glass ionomer cement produced higher stress concentration levels at the cement/dentin interface.
(3) The resin cement group presented fracture resistance values significantly higher than the other groups. The conventional glass ionomer group had intermediate fracture resistance values. The resin-modified glass ionomer and zinc–phosphate groups presented lower values for fracture resistance.

Acknowledgments

The authors are grateful to 3M ESPE, SS White, and Dentsply Maillefer for full donation of the materials used in this study.

References

1. Yu WJ, Kwon TY, Kyung HM, et al: An evaluation of localized debonding between fiber post and root canal wall by finite element simulation. Int Endod J 2006;39:959–967
2. Assif D, Gorfil C: Biomechanical considerations in restoring endodontically treated teeth. J Prosthet Dent 1994;71:565–567
3. Morgano SM, Brackett SE: Foundation restorations in fixed prosthodontics: current knowledge and future needs. J Prosthet Dent 1999;82:643-657
4. Schwartz RS, Robbins JW: Post placement and restoration of endodontically treated teeth: a literature review. J Endod 2004;30:289-301
5. Walton TR: An up to 15-year longitudinal study of 515 metal-ceramic FPDs: Part 2. Modes of failure and influence of various clinical characteristics. Int J Prosthodont 2003;16:177-182
6. Weine FS, Wax AH, Wenckus CS: Retrospective study of tapered, smooth post systems in place for 10 years or more. J Endod 1991;17:293-297
7. Mannocci F, Ferrari M, Watson TF: Intermittent loading of teeth restored using quartz fiber, carbon-quartz fiber, and zirconium dioxide ceramic root canal posts. J Adhes Dent 1999;1:153-158
8. Akkayan B, Gulmez T: Resistance to fracture of endodontically treated teeth restored with different post systems. J Prosthet Dent 2002;87:431-437
9. Torbjörner A, Fransson B: A literature review on the prosthetic treatment of structurally compromised teeth. Int J Prosthodont 2004;17:369-376
10. Naumann M, Blankenstein F, Dietrich T: Survival of glass fiber reinforced composite post restorations after 2 years—an observational clinical study. J Dent 2005;33:305-312
11. Zarone F, Sorrentino R, Apicella D, et al: Evaluation of the biomechanical behavior of maxillary central incisors restored by means of endocrowns compared to a natural tooth: a 3D static linear finite elements analysis. Dent Mater 2006;22:1035-1044
12. Zhi-Yue L, Yu-Xing Z: Effects of post-core design and ferrule on fracture resistance of endodontically treated maxillary central incisors. J Prosthet Dent 2003;89:368-373
13. Kishen A, Kumar GV, Chen NN: Stress-strain response in human dentine: rethinking fracture predilection in post-core restored teeth. Dent Traumatol 2004;20:90-100
14. Felton DA, Webb EL, Kanoy BE, et al: Threaded endodontic dowels: effect of postdesign on incidence of root fracture. J Prosthet Dent 1991;65:179-187
15. Standlee JP, Caputo AA, Collard EW, et al: Analysis of stress distribution by endodontic posts. Oral Surg Oral Med Oral Pathol 1972;33:952-960
16. Habib B, von Fraunhofer JA, Driscoll CF: Comparison of two luting agents used for the retention of cast dowel and cores. J Prosthodont 2005;14:164-169
17. Fleming GJ, Marquis PM, Shortall AC: The influence of clinically induced variability on the distribution of compressive fracture strengths of a hand-mixed zinc phosphate dental cement. Dent Mater 1999;15:87-97
18. Bouillaguet S, Troesch S, Wataha JC, et al: Microtensile bond strength between adhesive cements and root canal dentin. Dent Mater 2003;19:199-205
19. Mendoza DB, Eakle WS: Retention of posts cemented with various dentinal bonding cements. J Prosthet Dent 1994;72:591-594
20. Miller BH, Nakajima H, Powers JM, et al: Bond strength between cements and metals used for endodontic posts. Dent Mater 1998;14:312-320
21. Duncan JP, Pameijer CH: Retention of parallel-sided titanium posts cemented with six luting agents: an in vitro study. J Prosthet Dent 1998;80:423-428
22. Terata R, Nakashima K, Kubota M: Effect of temporary materials on bond strength of resin-modified glass-ionomer luting cements to teeth. Am J Dent 2000;13:209-211
23. Ertugrul HZ, Ismail YH: An in vitro comparison of cast metal dowel retention using various luting agents and tensile loading. J Prosthet Dent 2005;93:446-452
24. Eskitascioglu G, Belli S, Kalkan M: Evaluation of two postcore systems using two different methods (fracture strength test and a finite elemental stress analysis). J Endod 2002;28:629-633
25. Hu YH, Pang LC, Hsu CC, et al: Fracture resistance of endodontically treated anterior teeth restored with four post-and-core systems. Quintessence Int 2003;34:349-353
26. Saupe WA, Gluskin AH, Radke RA, Jr.: A comparative study of fracture resistance between morphologic dowel and cores and a resin-reinforced dowel system in the intra-radicular restoration of structurally compromised roots. Quintessence Int 1996;27:483-491
27. Soares PV, Santos-Filho PC, Martins LR, et al: Influence of restorative technique on the biomechanical behavior of endodontically treated maxillary premolars. Part I: Fracture resistance and fracture mode. J Prosthet Dent 2008;99:30-37
28. Versluis A, Messer HH, Pintado MR: Changes in compaction stress distributions in roots resulting from canal preparation. Int Endod J 2006;39:931–939
29. Ichim I, Kuzmanovic DV, Love RM: A finite element analysis of ferrule design on restoration resistance and distribution of stress within a root. Int Endod J 2006;39:443-452
30. Soares PV, Santos-Filho PC, Gomide HA, et al: Influence of restorative technique on the biomechanical behavior of endodontically treated maxillary premolars. Part II: strain measurement and stress distribution. J Prosthet Dent 2008;99:114-122

31. Gu XH, Kern M: Fracture resistance of crowned incisors with different post systems and luting agents. J Oral Rehabil 2006;33:918-923
32. Qing H, Zhu Z, Chao Y, et al: In vitro evaluation of the fracture resistance of anterior endodontically treated teeth restored with glass fiber and zircon posts. J Prosthet Dent 2007;97: 93-98
33. Mezzomo E, Massa F, Libera SD: Fracture resistance of teeth restored with two different post-and-core designs cemented with two different cements: an in vitro study. Part I. Quintessence Int 2003;34:301-306
34. Mezzomo E, Massa F, Suzuki RM: Fracture resistance of teeth restored with 2 different post-and-core designs fixed with 2 different luting cements: an in vitro study. Part II. Quintessence Int 2006;37:477-484
35. Soares CJ, Santana FR, Silva NR, et al: Influence of the endodontic treatment on mechanical properties of root dentin. J Endod 2007;33:603-606
36. Soares CJ, Pizi EC, Fonseca RB, et al: Influence of root embedment material and periodontal ligament simulation on fracture resistance tests. Braz Oral Res 2005;19:11-16
37. Dong CC, McComb D, Anderson JD, et al: Effect of mode of polymerization of bonding agent on shear bond strength of auto-cured resin composite luting cements. J Can Dent Assoc 2003;69:229-234
38. Akkayan B, Gulmez T: Resistance to fracture of endodontically treated teeth restored with different post systems. J Prosthet Dent 2002;87:431-437
39. Vichi A, Grandini S, Davidson CL, et al: An SEM evaluation of several adhesive systems used for bonding fiber posts under clinical conditions. Dent Mater 2002;18:495-502
40. Balbosh A, Ludwig K, Kern M: Comparison of titanium dowel retention using four different luting agents. J Prosthet Dent 2005;94:227-233
41. Nakamura T, Ohyama T, Waki T, et al: Stress analysis of endodontically treated anterior teeth restored with different types of post material. Dent Mater J 2006;25:145-150
42. Akkayan B: An in vitro study evaluating the effect of ferrule length on fracture resistance of endodontically treated teeth restored with fiber-reinforced and zirconia dowel systems. J Prosthet Dent 2004;92:155-162
43. Goto Y, Nicholls JI, Phillips KM, et al: Fatigue resistance of endodontically treated teeth restored with three dowel-and-core systems. J Prosthet Dent 2005;93:45-50
44. Holmes DC, Diaz-Arnold AM, Leary JM: Influence of post dimension on stress distribution in dentin. J Prosthet Dent 1996;75:140-147
45. Stafford CM, Harrison C, Beers KL, et al: A buckling-based metrology for measuring the elastic moduli of polymeric thin films. Nat Mater 2004;3:545-550
46. Attar N, Tam LE, McComb D: Mechanical and physical properties of contemporary dental luting agents. J Prosthet Dent 2003;89:127-134
47. Ichim I, Schmidlin PR, Kieser JA, et al: Mechanical evaluation of cervical glass-ionomer restorations: 3D finite element study. J Dent 2007;35:28-35
48. Li ZC, White SN: Mechanical properties of dental luting cements. J Prosthet Dent 1999;81:597-609