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

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Statement of problem. There are few published studies analyzing the effects of different ferrule lengths of endodontically treated teeth in relationship to newly developed fiber-reinforced and zirconia dowel systems.

Purpose. This in vitro study compared the effect of 3 different ferrule lengths on the fracture resistance and fracture patterns of crowned endodontically treated teeth restored with 4 different esthetic dowel systems.

Material and methods. The crowns of 123 human maxillary canines were removed at the cementoenamel junction and the roots were endodontically treated. Three master tooth models were prepared to ferrule lengths of 1.0 mm, 1.5 mm, and 2.0 mm to produce 3 master analogs. Each root was embedded in autopolymerizing resin with a 0.2-mm layer of silicone impression material to simulate the periodontal ligament. Forty analogs of each master tooth, with ferrule lengths of 1.0 mm, 1.5 mm, and 2.0 mm were produced with copy-milling (Celay system). Each group was further subdivided into 4 groups of 10 specimens each and restored with 4 different esthetic dowel systems (quartz fiber, glass fiber, glass fiber plus zirconia, and zirconia). All dowels were luted with adhesive resin cement (RelyX ARC), restored with composite cores (Valux Plus), and Ni-Cr alloy (Wiron 99) complete crowns. All specimens were loaded at 130 degrees to the long axes in a universal testing machine at a crosshead speed of 1 mm/min until fracture. Fracture patterns were classified as failures above or below the incisal third of the roots. The data were analyzed with 2-way ANOVA and Tukey HSD tests (α=.05). A Fisher exact test was conducted for evaluation of the mode of failure (α=.05).

Results. Mean failure loads (kg) for quartz fiber, glass fiber, glass fiber plus zirconia, and zirconia groups, respectively, with the 3 ferrule lengths were: 1.0-mm ferrule specimens: 98.09 ± 2.90, 85.36 ± 2.82, 80.24 ± 1.88, 70.11 ± 2.48; 1.5-mm ferrule specimens: 101.0 ± 2.88, 87.58 ± 2.83, 89.8 ± 2.09, 82.71 ± 2.14; 2.0-mm ferrule specimens: 119.5±1.78, 99.84±1.23, 98.6 ± 1.64, 95.42 ± 1.02. Teeth prepared with 2.0-mm ferrules demonstrated significantly higher fracture thresholds (*P*<.001). There were no significant differences in fracture patterns.

Conclusion. Increasing the ferrule length of the endodontically treated teeth from 1 mm to 1.5 mm in specimens restored with quartz-fiber and glass-fiber dowels did not produce significant increases in the failure loads (*P*=.084, *P*=.119, respectively). No significant difference was detected between glass-fiber and glass-fiber plus zirconia dowels with 1.5-mm and 2.0-mm ferrules (*P*=.218, *P*=.244, respectively). However, fracture thresholds were higher for all 4 dowel systems when the specimens were prepared with a 2.0-mm ferrule length (*P*<.001). (J Prosthet Dent 2004;92:155-62.)

CLINICAL IMPLICATIONS

Under the conditions of this in vitro study, a 2.0-mm ferrule preparation increased the fracture resistance of endodontically treated teeth regardless of the dowel system tested. This in vitro study confirms the results of other studies and suggests that a 2-mm ferrule is a rational clinical guideline for the restoration of pulpless teeth.

Dowels were originally designed to retain the coronal restoration when inadequate tooth structure remained.[1] Dowels were later viewed as a method of reinforcing endodontically treated teeth.[2] Rigid cast metal dowels and cores have been advocated by some clinicians as the restorative method of choice for endodontically treated teeth.[3] However, the growing demand for esthetic restorations in dentistry has led to the development of tooth-colored, metal-free, dowel-and-core systems.[4] Martinez-Insua et al[5] suggested that restoration of endodontically treated teeth was an important preventive measure because failure to do so could result in recurrent dental caries or destructive root fractures. Although the authors stated that the dowels and cores used for the restoration of endodontically

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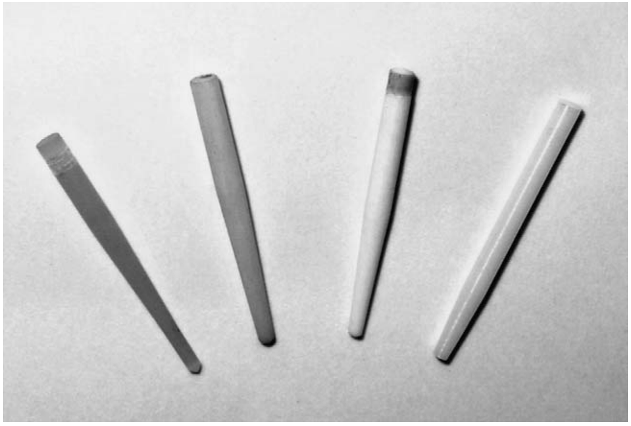

Fig. 1. Dowel systems *(left to right)* D.T. Light-Post, ERDentin-Post, EasyPost, and CosmoPost.

treated teeth should be strong, they also indicated that it is preferable for the dowel to fail before the remaining dental structure in response to mechanical stress.

As dentin is removed during preparation of the dowel space, reduction in fracture resistance may outweigh any likely gains associated with the dowel. Nevertheless, horizontal loss of the clinical crown of an endodontically treated tooth occurs, commonly, with minimal ferrule in the remaining tooth structure.[6,7] Trope et al[8] noted that a dowel and core in an endodontically treated tooth could transfer occlusal forces intraradicularly with resultant predisposition to vertical fracture of the root. Sorensen and Engelman[6] proposed that the preparation design of endodontically treated teeth was a critical consideration, but this topic has received limited attention.

Libman and Nicholls[7] stated that the marginal area of a crown should extend onto the tooth structure 1.5 to 2 mm beyond the core material to produce an adequate ferrule. Sorensen and Engelman[6] described the ferrule as the coronal dentinal extension of the tooth structure occlusal to the shoulder preparation. Sorensen[9] and other authors[7,10,11] suggested either a crown lengthening procedure or orthodontic extrusion of the tooth if no supragingival coronal tooth structure remained. Sorensen and Engelman[6] also reported that gaining at least 1.0 mm of coronal tooth structure above the shoulder of a beveled crown preparation doubled the fracture resistance of teeth restored with cast dowels and cores. Trabert and Cooney[12] and Assif et al[13] suggested that the crown should extend 2 mm beyond the tooth-core junction to ensure a protective ferrule effect. Morgano and Brackett[14] recommended a minimal height of 1.5 to 2 mm of intact tooth structure above the crown margin for 360 degrees around the circumference of the tooth preparation as a rational guideline for the ferrule effect. Morgano and Brackett[14] also suggested that when the ferrule was absent, occlusal forces would become concentrated at the junction of the dowel and the core with potential for dowel fracture.

Heydecke et al[15] reported that the choice of an appropriate restoration for endodontically treated teeth is guided by strength and esthetics. With recent advances in ceramic technology, all-ceramic crowns have become more popular. Sorensen and Mito[16] suggested that a dowel-core restoration supporting a translucent all-ceramic crown should not adversely affect the esthetic qualities of the definitive restoration. New tooth-colored dowels can potentially improve the esthetics of teeth restored with dowels and cores.[17-19] Zirconia dowels were developed in the late 1980s in response to the need for a dowel that possessed optical properties compatible with an all-ceramic crown.[20,21] The dowel was made from fine-grain dense tetragonal zirconium polycrystals (TZP), and the zirconia dowel has been reported to possess high flexural strength and fracture toughness.[20,22,23] Glass- and quartz-fiber-reinforced dowel systems, with elastic moduli comparable to that of dentin, were later introduced.[24,25] Freedman[26] reported that the types of failure that occurred with these dowel systems were primarily dowel-and-core fractures that could potentially allow retreatment of the tooth. Translucent quartz-fiber dowel systems recently were introduced as a method to achieve optimal esthetics. These dowels allowed the use of light-polymerized luting agents.[17]

Asmussen et al[27] suggested that mechanical properties of dowel systems should be considered when investigating the causes of failure in endodontically treated crowned teeth. The restoration of endodontically treated teeth with metal-free materials having physical properties similar to those of dentin has been suggested as an objective in restorative dentistry.[28] Christensen[29] reported that physical properties of dowel systems became more important as residual intact tooth structure decreased. Manocci et al[17] investigated the intermittent loading response of teeth restored with quartz-fiber, carbon-quartz fiber, and zirconium dowels and concluded that the fiber dowels were able to reduce the risk of root fractures. Butz et al[19] stated that teeth restored with zirconia dowels and heat-pressed ceramic cores exhibited less vertical fractures compared with teeth restored by using zirconia dowels and composite cores. In another recent study, quartz-fiber dowels were found less prone to cause root fractures compared with the titanium, glass-fiber, and zirconia dowels tested.[18] Rosentritt et al[30] reported that fiber-reinforced dowels with composite cores achieved a fracture strength that was not significantly different from the gold alloy control group. However, loss of the cement seal of an artificial crown can occur with a "flexible" dowel.[14] Freeman et al[31] reported that this loss of the cement seal of the coronal restoration was clinically undetectable initially; nevertheless, leakage occurred between the crown margin and the tooth surface, potentially leading to dental caries and loss of the tooth. The purpose of this study was to compare the fracture resistance and mode of fracture of endodontically treated teeth prepared with 3 different ferrule lengths—1.0 mm, 1.5 mm, and 2.0 mm—and restored with zirconia and 4 newly developed fiber-reinforced esthetic dowel systems (Fig. 1).

MATERIAL AND METHODS

One hundred twenty-three freshly extracted canines free of cracks, caries, fractures, and restorations were selected for the study. All external debris was removed with an ultrasonic scaler (Mini Piezon; EMS Piezon Systems, Nyon, Switzerland), and the teeth were stored in saline solution until testing. The anatomic crowns of all teeth were removed perpendicular to the long axis of the tooth, from the most incisal point of the approximal cementoenamel junction (CEJ), with the use of a water-cooled diamond stone (R837.014; Diaswiss, Geneva, Switzerland) and an air turbine (Midwest 8000; Dentsply, York, Pa) at 300,000 rpm. The root lengths were measured from the CEJs on the facial surfaces, and the widest faciolingual and mesiodistal dimensions of each specimen were determined with a digital caliper accurate to 1 μm (Digimatic Calipers Model 500-196; Mitutoyo Corp, Aurora, Ill). The teeth were assigned randomly to 12 groups of 10 teeth each. The root dimensions were assessed with 2-way analysis of variance (ANOVA), and no significant differences among the measurements for the various groups were found (α=.05). The specimens were then endodontically prepared with a step-back procedure with a size 55 file (Flex R File; Union Broach, York, Pa). After intermittent rinsing with 2.5% sodium hypochlorite, the endodontic treatment was completed with lateral condensation of gutta-percha (Gutta Percha Points; United Dental Manufacturers, West Palm Beach, Fla) and eugenol-free sealer (AH 26; Dentsply DeTrey, Konstanz, Germany).

Three maxillary canines were randomly selected from the experimental teeth, were prepared to ferrule lengths of 1.0 mm, 1.5 mm, and 2.0 mm, respectively, as master tooth models, and received 1.2 mm shoulder finish lines (837KR314.012 and 8837KR314.012; Komet-Brasseler, Lemgo, Germany). The 3 prepared teeth were then embedded in silicone (Rhodorsil; Rhone-Poulenc, Lyon, France). All were removed after the silicone had polymerized, and autopolymerizing acrylic resin (Pattern Resin; GC Corp, Tokyo, Japan) was injected into the impression cavities to produce acrylic resin patterns of the master tooth models. Patterns were embedded in silicone impression material (Speedex putty; Coltene, Alstatten, Switzerland) to 12 mm from the tip of the roots and attached to a milling machine (Paraskop M; Bego, Bremen, Germany). The patterns were milled with a 6-degree milling cutter (18.00. 26060; Bego) to establish a 6-degree taper of opposing walls and a 12-degree convergence angle. Prepared master acrylic resin patterns were cast in Ni-Cr alloy (Wiron 99; Bego). The experimental teeth and the 3 cast master models were then stabilized on a specimen holder (Bego) with vertically moving rods, from the center of each canal, with sticky wax (Pico sticky wax; Renfert, Hilzingen, Germany). Root surfaces were marked 3 mm below the CEJ and covered with 2 layers of 0.1-mm foil (Adapta System; Bego). Specimens were then lowered into the center of a machined aluminum cylinder and retained with autopolymerizing acrylic resin (Meliodent; Bayer Dental; Newbury, UK). After the first signs of polymerization, teeth were removed

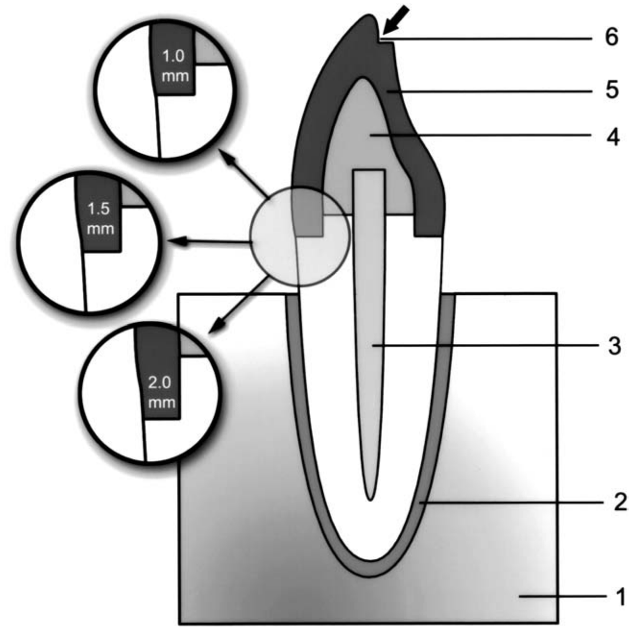

Fig. 2. Schematic drawing of specimen mounted in acrylic resin block and illustration of ferrule effect: *1*, resin block, *2*, silicone simulated periodontal ligament, *3*, prefabricated dowel, *4*, composite core, *5*, cemented metal crown, and *6*, arrow indicating 130-degree angle load applied to prepared step on palatal surface.

Table I. Description of dowel systems

Product name	Manufacturer	Composition*
D.T. Light-Post	Recherches Techniques Dentaires, St. Egreve, France	Quartz fiber
ER DentinPost	Brasseler-Komet, Lemgo, Germany	Glass fiber
EasyPost	Dentsply-Maillefer, Ballaigues, Switzerland	Glass fiber + zirconia
CosmoPost	Ivoclar Vivadent, Schaan, Liechtenstein	Zirconia

*According to manufacturer.

Table II. Mean failure loads (kg) of experimental groups

	Dowel types			
Ferrule lengths	Quartz fiber	Glass fiber	Glass fiber + zirconia	Zirconia
1.0-mm ferrule	98.09 ±2.90	85.36 ± 2.82	80.24 ± 1.88	70.11 ± 2.48
1.5-mm ferrule	101 ± 2.88	87.58 ± 2.83	89.8 ± 2.09	82.71 ± 2.14
2.0-mm ferrule	119.5 ± 1.78	99.84 ± 1.23	98.6 ± 1.64	95.42 ± 1.02

Table III. Two-way ANOVA for 2 main effects: dowels and ferrule lengths

Source	*df*	Sum of squares	Mean square	F	*P* value
Ferrule length	2	8176.221	4088.110	818.265	.0001*
Dowel	3	8823.468	2941.156	588.693	.0001*
Ferrule length/dowel	6	630.850	105.142	21.045	.0001*
Error	108	539.576	4.996		

*Significant difference at α=.05

Table IV. Significant differences within groups as identified with Tukey HSD test (α=.05)

Ferrule length	Quartz fiber	Glass fiber	Glass fiber + zirconia	Zirconia
1.0-mm/1.5-mm ferrule	*P*=.084	*P*=.119	*P*<.001	*P*<.001
1.0-mm/2.0-mm ferrule	*P*<.001	*P*<.001	*P*<.001	*P*<.001
1.5-mm/2.0-mm ferrule	*P*<.001	*P*<.001	*P*<.001	*P*<.001

Table V. Significant differences between groups as identified with Tukey HSD test (α=.05)

Dowel type	1.0-mm ferrule	1.5-mm ferrule	2.0-mm ferrule
Quartz fiber/glass fiber	*P*<.001	*P*<.001	*P*<.001
Quartz fiber/glass fiber + zirconia	*P*<.001	*P*<.001	*P*<.001
Quartz fiber/zirconia	*P*<.001	*P*<.001	*P*<.001
Glass fiber/glass fiber + zirconia	*P*<.001	*P*=.218	*P*=.244
Glass fiber/zirconia	*P*<.001	*P*<.001	*P*<.001
Glass fiber + zirconia/zirconia	*P*<.001	*P*<.001	*P*<.001

from the resin blocks by moving the rods in an upward direction, and the foil spacers were removed from the root surfaces. Silicone impression material (Speedex light body; Coltene) was injected into the acrylic resin molds, and the teeth were reinserted into the resin cylinders to produce standardized silicone layers that simulated periodontal ligaments.

Copy-milling technology (Celay system; Mikrona, Spreitenbach, Switzerland) and the method described by Gur et al[32] were used for the production of 3 groups of 40 analog specimens with 3 different ferrule lengths of 1.0 mm, 1.5 mm, and 2.0 mm (Fig. 2). The working principle of the Celay apparatus is that movements are transferred synchronously to the milling compartment where, with the use of rotary instruments, the surface characteristics of the cast master tooth model are reproduced on the natural tooth specimens.[32] The resin-retained master tooth with a 1.0-mm ferrule length, surrounded by the aluminum cylinder, was attached in the copying chamber, and a tooth specimen embedded in acrylic resin was attached to the milling chamber of Celay apparatus. Thus, 40 analog tooth specimens of each master tooth were produced. Each group was further divided into 4 subgroups of 10 analog teeth each. The dowel systems used are listed in Table I.

The lengths of the 4 dowel systems measured 20 mm. Each dowel was marked at a distance of 15 mm from its apical end. A line was drawn around the dowel at this level, and all dowels were sectioned horizontally with a water-cooled diamond fissure stone (R879.014; Diaswiss). This established a similar diameter of 1.70 mm for the 4 tapered dowel systems used in this study. Gutta-percha was removed from the root canals with a reamer (Peeso Reamer; Dentsply-Maillefer, Ballaigues, Switzerland) leaving 4 mm of the endodontic filling in the apical portion, and dowel spaces were prepared in all groups with the special preparation burs of each system.

All dowels were luted with an adhesive system (Single Bond Dental Adhesive; 3M Dental Products, St Paul, Minn) and dual-polymerizing adhesive resin luting agent (RelyX ARC; 3M Dental Products) according to the manufacturer's guidelines. The walls of the root canal were etched with 35% phosphoric acid (Scotchbond etchant; 3M Dental Products) for 15 seconds, washed with water spray, and gently air dried. Two consecutive coats of adhesive were applied in the canals. After the material had dried for 5 seconds, excess was removed with a dry paper point, and the adhesive was light-polymerized for 10 seconds, with the tip of the light unit (Optilux 501; Kerr/Demetron Research Corp, Danbury, Conn) directly in contact with each dowel space. The intensity of light produced was 800 mW/cm^2, and it was measured with the built-in digital radiometer of the light unit before each exposure to ensure accurate light intensity. A dual-polymerizing adhesive resin luting agent was mixed for 10 seconds and

Table VI. Number of root fractures according to localization for each group

	Quartz fiber			Glass fiber			Glass fiber + zirconia			Zirconia		
	Ferrule length (mm)			Ferrule length (mm)*			Ferrule length (mm)			Ferrule length (mm)		
	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0	1.0	1.5	2.0
Above incisal third*	8	8	10	6	6	8	4	5	6	3	5	6
Below incisal third†	2	2	0	4	4	2	6	5	4	7	5	4

*Fractures located in incisal third of root.
†Fractures located below incisal third of root.

applied in the canal walls with the use of a periodontal probe. A thin layer of cement also was placed on the dowel surface, and the dowel was inserted in the canal. Excess cement was removed. The coronal end of each dowel was positioned directly in contact with the tip of the light unit and was light polymerized for 40 seconds.

Dentin was prepared with the use of the Single Bond adhesive system. A light-polymerized composite core (Valux Plus; 3M Dental Products) was fabricated on 1 of the specimens, and a crown preparation was completed on the composite core material with the use of a water-cooled diamond stone (6862-314.012; Komet-Brasseler). The core portion of the dowel and core restoration was 6.0 mm in height. A matrix was formed on the core with 0.6-mm foil (Adapta System; Bego). The matrix was filled with the composite material, seated on the root of another specimen along the long axis, and light-polymerized for 40 seconds from facial and lingual surfaces with a light unit (800 mW/cm^2). All other composite cores were produced with the same procedure. One coat of die relief (Picosep; Renfert) was applied on the composite core.

Preheated liquid wax (Pico Sculpturing Wax; Renfert) was inserted into a size 35 polycarbonate crown (Polycarbonate Crown Forms; 3M Dental Products) with the use of modeling tips (Waxelectric; Renfert), and the crown was seated directly on the core along the long axis. After cooling of the wax, excess wax was removed and the polycarbonate crown was removed. The same procedure was used for all specimens. A marking line was scraped 3 mm below the incisal edge of the canine wax pattern on the palatal surface. A palatal step design (0.3 mm deep and 1 mm wide) was formed on each specimen. The wax patterns for the crowns were custom cast with a Ni-Cr alloy (Wiron 99; Bego), and luted to the cores with resin-modified glass ionomer cement (Vitremer Luting Cement; 3M Dental Products).

Specimens were secured in a universal testing machine (HA 100; Dartec, Surrey, UK) with the use of a device that allowed loading of the tooth lingually at 130 degrees to the long axis. The load head was placed on the specially formed palatal step. A compressive force was applied at a crosshead speed of 1 mm/min until fracture occurred. The fracture loads (kg) were determined and the obtained data were analyzed by 2-way ANOVA with interaction followed by Tukey HSD tests (SPSS/PC, Version 9.0; SPSS, Chicago, Ill). The mode of fracture also was recorded, and the fractures were classified whether located below or above the incisal third of the roots. A Fisher exact test was performed to detect within- and between-group differences in fracture modes. No adjustment to the alpha level was made when performing the multiple Fisher exact tests. A significance level of α=.05 was used for all comparisons.

Table VII. Significant differences in fracture patterns within groups as identified with Fisher exact test (α=.05)

Ferrule length	Quartz fiber	Glass fiber	Glass fiber + zirconia	Zirconia
1.0-mm/1.5-mm ferrule	1.000	1.000	1.000	0.649
1.0-mm/2.0-mm ferrule	0.473	0.628	0.654	0.369
1.5-mm/2.0-mm ferrule	0.473	0.628	1.000	1.000

RESULTS

Mean failure loads were calculated for all groups (Table II). Two-way ANOVA was performed to test the 2 main effects, dowels, and ferrule lengths on the fracture strength. The result of the analysis revealed a significant difference in both the main effect dowel (P<.0001) and ferrule length (P<.0001). Significant dowel by ferrule-length interaction was also encountered (P<.0001) (Table III).

Further analysis with the Tukey HSD test indicated that the within-group differences for all dowel specimens were statistically significant (P<.0001) except for quartz-fiber and glass-fiber groups with 1.0-mm ferrule and 1.5-mm ferrule (P=.084, P=.119, respectively) (Table IV). Between-group differences were also identified with Tukey HSD tests and are presented in Table V. The group with 1.0-mm ferrule length and quartz-fiber dowel received significantly higher loads (98.09 ± 2.90 kg) before failure than teeth with the combinations of 1.0-mm ferrule length and glass fiber (85.36 ± 2.82 kg), glass fiber plus zirconia (80.24 ± 1.88 kg), and zirconia (70.11 ± 2.48 kg) (P<.001). Teeth with 1.5-mm ferrule and restored with quartz

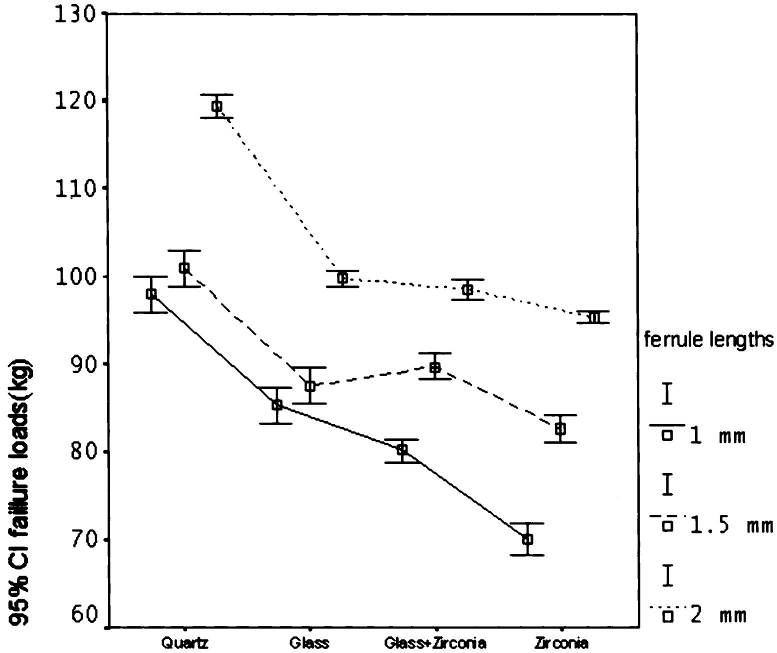

Fig. 3. Failure thresholds for specimens prepared at ferrule lengths of 1.0 mm, 1.5 mm, and 2.0 mm, and restored with 4 different dowel systems.

fiber dowels fractured at 101.0 ± 2.88 kg and were significantly more resistant to fracture than glass fiber (87.58 ± 2.83 kg), glass fiber plus zirconia (89.8 ± 2.09 kg), and zirconia (82.71 ± 2.14) ($P<.001$). No significant difference was detected between glass-fiber and glass-fiber plus zirconia dowel systems with 1.5-mm ferrule length ($P=.218$). The highest fracture resistance was recorded for teeth with 2.0-mm ferrules for all of the dowel groups (Fig. 3), for quartz fiber at 119.5 ± 1.78 kg, followed by glass fiber at 99.84 ± 1.23 kg, glass fiber + zirconia at 98.6 ± 1.64 kg, and zirconia at 95.42 ± 1.02 kg. No significant difference was detected between glass-fiber and glass-fiber plus zirconia dowel systems with 2.0-mm ferrule length ($P=.244$).

Differences regarding the mode of failure among the different dowels and at different ferrule lengths were observed and analyzed. Fracture patterns were classified according to location, as incisal third of the root or below (Table VI). A Fisher exact test detected no significant differences in fracture patterns within and between groups (Tables VII and VIII). The fracture patterns of all groups are presented in Figure 4.

DISCUSSION

In the present study, 2-way ANOVA was used to test the 2 main effects on the fracture resistance of endodontically treated teeth restored with 4 esthetic dowel systems and 3 different ferrule lengths. Significant within-group differences were observed for all subgroups except for the quartz-fiber groups with 1.0-mm and 1.5-mm ferrule lengths ($P=.084$) and glass-fiber groups with 1.0-mm and 1.5-mm ferrule lengths ($P=.119$). The low elastic modulus of quartz- and glass-reinforced dowels, which approaches the elastic modulus of dentin, may explain the similar fracture resistance values observed in endodontically treated teeth prepared with either 1.0- or 1.5-mm ferrule lengths.

In the glass fiber plus zirconia and zirconia groups, significant within-group differences were noted among ferrule lengths of 1.0 mm, 1.5 mm, and 2.0 mm. This observation may be attributable to the variation in mechanical properties of these dowel systems, especially those with higher elastic moduli. This phenomenon was also reported in previous studies.[15,19] Relatively low fracture strength and fracture toughness are the primary obstacles for routine use of ceramics as dowel materials.[23] Zirconia dowels have been fabricated with improved mechanical properties of increased flexural strength and fracture toughness.[20] However, in the present study, the lowest mean failure loads were recorded for the zirconia dowel groups, regardless of the 3 ferrule lengths prepared, and all zirconia dowels fractured (Fig. 4). In a study of zirconia dowels with composite cores, Rosentritt et al[30] reported that the bond between the core material occurred first followed by fracture of the dowels. Clinically, it would be extremely difficult to remove these zirconia dowels if fractured within the root. It may be suggested that if a rigid dowel system is used, a ferrule length of 2.0 mm would improve the long-term prognosis of the endodontically treated tooth.

Variations were observed in between-group comparisons of the present study. Significant differences were observed in endodontically treated teeth prepared with different ferrule lengths of 1.0-mm, 1.5-mm, and 2.0-mm and restored with quartz dowels compared to the other 3 esthetic dowel systems. This result may be attributable to the modulus elasticity of the quartz-fiber dowels, which is closest to that of natural teeth among the dowel types tested. In a previous study of 4 dowel systems that did not incorporate a ferrule, quartz-fiber dowels were less likely to cause root fracture followed by glass-fiber dowels.[18]

The findings of the present study indicated that the fracture thresholds were higher for all 4 dowel systems when the specimens were prepared with a 2-mm ferrule length ($P<.001$). Libman and Nicholls[7] evaluated in vitro effects of ferrules on the integrity of the cement seal of cast crowns and reported improved resistance to fatigue failure of the cement seal of a crown when the crown margin extended at least 1.5 mm apical to the margin of the core. Morgano and Brackett[14] reported that a flexible dowel could be detrimental especially when there was little remaining natural tooth structure between the margin of the core and the gingival extension of the artificial crown. When the ferrule is absent or extremely small, occlusal loads may cause the dowel to flex with eventual micromovement of the core, and the cement seal at the margin of the crown may fracture in a short time with resultant leakage and caries.[14,31] It has been reported also that contact with intraoral fluids might produce flexure of fiber-reinforced dowels, with the subsequent risk of secondary caries.[4,28] Under the conditions of this in vitro study, 2.0-mm ferrule preparation increased the fracture resistance of endodontically treated teeth regardless of the dowel system tested ($P<.001$) (Fig. 3). Fracture patterns were classified as failures above or below the incisal third of the roots. Differences between the groups in the present study were not significant (Table IX); perhaps because of the limited sample size.

Because there was a limited number of specimens in this study, it is impossible to draw definitive conclusions on the failure modes. It must also be noted that this study did not address the biologic effects of failure of the cement seal of the artificial crown. Also, specimens were statically loaded without thermal cycling, and this experimental design may be a limitation to the direct application of these vitro results to in vivo situations.

CONCLUSIONS

Within the limitations of this in vitro study, the following conclusions were drawn.

Table VIII. Significant differences in fracture patterns between groups as identified with Fisher exact test (α=.05)

Dowel type	1.0-mm ferrule	1.5-mm ferrule	2.0-mm ferrule
Quartz fiber /glass fiber	0.628	0.628	0.473
Quartz fiber/glass fiber + zirconia	0.169	0.349	0.086
Quartz fiber/zirconia	0.069	0.349	0.086
Glass fiber/glass fiber+ zirconia	0.654	1.000	0.628
Glass fiber/zirconia	0.369	1.000	0.628
Glass fiber + zirconia/ zirconia	1.000	1.000	1.000

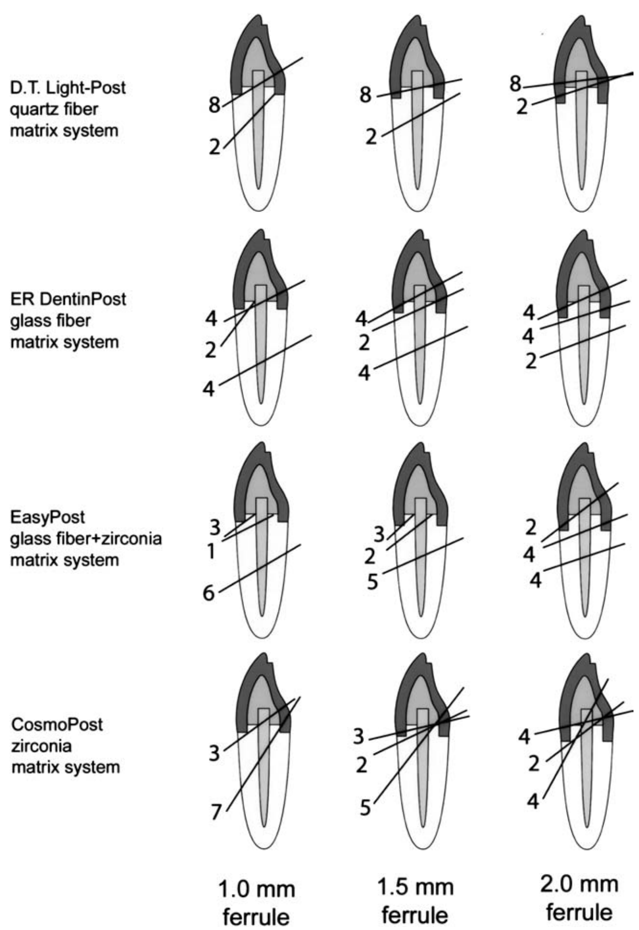

Fig. 4. Locations and frequencies of fractures in 4 test groups.

1. There was a significant difference in the mean fracture loads of endodontically treated teeth prepared to 2.0-mm ferrule length compared with 1.0-mm and 1.5-mm ferrule lengths regardless of the dowel system tested ($P<.001$).

2. Among the 1.0-mm, 1.5-mm, and 2.0-mm ferrule-length specimens, significantly higher fracture loads were observed in teeth restored with quartz-fiber

dowels compared with teeth restored with the other 3 systems tested ($P<.001$).

3. There was no significant difference among the fracture loads of quartz-fiber groups with 1.0-mm and 1.5-mm ferrule lengths ($P=.084$) and glass-fiber groups with 1.0-mm and 1.5-mm ferrule lengths ($P=.119$).

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