# Fracture Strength and Nanoleakage of Weakened Roots Reconstructed Using Relined Glass Fiber–Reinforced Dowels Combined with a Novel Prefabricated Core System

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Flared roots; prefabricated core; silver nitrate; fracture resistance.

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## Abstract

**Purpose:** The aim of this study was to evaluate fracture strength and nanoleakage of endodontically treated weakened teeth after being restored with relined glass fiber–reinforced dowels and two types of cores.
**Materials and Methods:** Sixty sound human decoronated and endodontically treated teeth were embedded in epoxy resin blocks, then divided into three groups ($n = 20$) according to the method of root reconstruction. Group 1 (control): nonweakened roots were restored with glass fiber–reinforced dowels (UNIC); group 2: weakened roots restored with glass fiber–reinforced dowels relined with composite resin; group 3: weakened roots restored with glass fiber–reinforced dowels and a thick layer of luting cement. Dowels were cemented using Corposit, a dual-cured adhesive resin cement, then each group was assigned into two subgroups ($n = 10$) according to the type of core used; subgroup a: custom-made core using the same luting cement, subgroup b: prefabricated glass fiber–reinforced core (UNIC). Half the specimens of each subgroup were individually mounted at 45° angles and statically compressed until fracture at a 0.5 mm/min crosshead speed with a 5 kN load cell. The type of failure was assessed using a magnification lens. The other half of the specimens were removed from the block, placed in silver nitrate solution for 24 hours followed by photo developer for 8 hours, then examined using environmental scanning electron microscope/energy dispersive analytical X-ray for nanoleakage evaluation. Data were statistically analyzed.
**Results:** The nonweakened group recorded the highest fracture strength values. The composite relined group showed significantly higher fracture strength values than the cement group. The prefabricated core yielded higher fracture strength values than the custom-made core. All groups showed a degree of nanoleakage, with higher scores recorded for the composite group.
**Conclusions:** The fracture resistance of wide root canals can be improved by using glass fiber–reinforced dowels relined with composite resin as an alternative to increasing the thickness of luting cement; however, the percentage nanoleakage would increase. On the other hand, the recently introduced prefabricated glass fiber–reinforced core can be considered a promising technique, but further investigations are necessary.

The clinical success of fiber-reinforced dowels had been attributed to their modulus of elasticity, which matches that of dentin and resin luting cements. This reduces stress transmission to root canal walls and decreases the risk of vertical root fractures.[1] Moreover, glass fiber–reinforced dowels allow the construction of highly esthetic restorations when combined with all-ceramic extracoronal restorations.[2] However, despite the cited advantages, the mismatch between the diameters of the dowel space and the fiber-reinforced dowels presented a clinical problem.[3] Prefabricated dowels do not fit well into either noncircular[4] or excessively flared canals that may result from carious extension, trauma, pulpal pathosis, or canal preparation procedures.[3] In these cases, the remaining residual structure is a thin root wall that makes the restorative procedure more difficult and can compromise the prognosis for a long-term successful restoration of the tooth,[5] as tooth strength is directly related to the bulk of dentin tissue surrounding the dowel.[6]

Placing prefabricated fiber-reinforced dowels in excessively flared canals will result in an excessively thick cement layer. A thick cement layer will harbor more air bubbles and voids, which will act as crack raisers, decreasing dowel retention, leading eventually to the dowel's debonding.[7] Different materials and techniques have been proposed to minimize this problem through reconstructing the inner walls of the root canals.[8,9] The main objective of such reinforcement is the formation of an ideal "monoblock" restoration that creates a single biomechanical complex between the tooth structure and the prosthetic components (dowel, cement, restorative material).[10-13] This can be achieved by bonding and using materials with mechanical properties similar to those of the remaining root structure.[14] One of the proposed solutions is to reline fiber-reinforced dowels with composite resin.[8] However, none of the adhesive techniques proposed for weakened root reconstruction recovered the load resistance of structurally intact roots, suggesting that the thickness of the remaining dentin is the preponderant factor in maintaining resistance to fracture.[6,15] Moreover, endodontically treated teeth are usually presented with a significant loss of coronal tooth structure, necessitating abutment buildup around the fiber-reinforced dowels. Several dental materials have been proposed for core build-up procedures. The ease of use of direct materials dominates their selection. Improvement in composite resin technology and the development of new dentinal adhesive systems made resin composite the selected material in the restoration of nonvital teeth. Both packable and flowable composite build-up materials have been recently recommended for reducing the early failure rate of nonvital teeth.[16] Flowable resin composites achieved good results in terms of microscopic structural integrity and surface adaptation around fiber-reinforced dowels.[17,18] However, they are intrinsically weak due to their low modulus of elasticity, and are probably unable to offer sufficient resistance against occlusal load.[19]

The tooth structure, the dowel's luting agent, and core build-up material must be a sealed system.[20] If the coronal seal is disrupted, inadequate marginal adaptation of the luting agent may allow for recontamination of the root.[21] Microorganisms proliferate and take a few days to pass through the remaining apical filling.[20]

For years, "extent of microleakage" was used to evaluate the sealing ability of cemented restorations; however, in 1994, Sano et al[22] described a new pattern of microleakage that occurred in the absence of gaps and which resulted from subsurface porosity of demineralized dentin. This form of leakage was detected on a microscopic, as opposed to a macroscopic, level and was thus referred to as "nanoleakage."[23]

Nanoleakage is a leakage pattern occurring within the nanometer-sized spaces within the hybrid layer and the adhesive/resin interface.[24] According to Abo El Naga, nanoleakage "is an important indicator for judging the material's sealing ability and quality of the hybrid layer, which in turn affects the material's longevity. Although the amount of nanoleakage may be very small (nanometer-size) in the bonded assembly, it has the potential to serve as a pathway for water movement within the adhesive/resin interface over time. Therefore, the effect of nanoleakage on the integrity of resin/dentin bonding has become of interest not only for short-term, but especially for long-term adhesion."[25]

The aim of this study was to evaluate the fracture resistance and the nanoleakage of weakened roots restored using glass fiber-reinforced dowels reconstructed with composite resin combined with two types of cores: prefabricated and custom-made. The null hypotheses tested were: (1) there is no significant difference in fracture strength between nonweakened roots and weakened roots reconstructed with either composite resin or thick cement layer, combined with either prefabricated or custom-made cores. (2) There is no significant difference in nanoleakage between nonweakened roots and weakened roots reconstructed with either composite resin or cement, combined with either prefabricated or custom-made cores.

## Materials and methods

To conduct this study, 60 freshly extracted human maxillary central incisors were selected. The selected teeth had straight, anatomically similar roots, with fully developed apices, and approximately similar lengths and widths. The soft tissue covering the root surface was removed with an ultrasonic scaler (Suprasson PMax; Satelec/Acteon Equipment, Merignac, France). Teeth were immediately placed in 5.25% NaOCl for 5 minutes and then stored in saline solution at room temperature until use.

### Endodontic procedure

The teeth were decoronated by being cut perpendicular to their long axis, coronal to the labial cemento-enamel junction (CEJ) using a diamond double-faced disk (910D; Diatech; Coltène AG, Altstätten, Switzerland) mounted in a low-speed handpiece under water coolant. The working length was established directly by subtracting 1.0 mm from the real root length determined by introducing a number 10 K-file (Maillefer-Dentsply, Ballaigues, Switzerland) until it was visible through the apical foramen. Only roots with identical lengths (14 ± 0.5 mm) were accepted.

The pulp tissue was removed with a barbed broach (Pulp Dent Corporation, Watertown, MA). A step-back technique using K-files (Maillefer-Dentsply) was used for canal instrumentation. The same operator instrumented all root canals to the same size (size 50 file; Maillefer-Dentsply). During instrumentation, canals were irrigated with 1 ml of 0.5% NaOCl preceding the use of each instrument and then dried with sterile absorbent paper points (Maillefer-Dentsply). The canals were obturated with gutta-percha points (Maillefer-Dentsply) and eugenol-free sealer (Roeko, Coltene/Whaledent Gmbh + Co., Langenau, Germany) using the lateral condensation technique. Cervical root canal openings were then filled with a provisional restorative material (Cavit-G; 3M ESPE, Seefeld, Germany), and the gutta-percha-filled roots were placed in a humidor (100% relative humidity) for 1 week at 37°C.

An epoxy resin (Kemapoxy, CMB; Giza, Egypt) block was constructed to fix each prepared root in a vertical position. A special cylindrical stainless steel root block former (20 mm length, 15 mm diameter) was machined to construct the sample block. A vertical holding device was used to ensure placement of the root in a vertical position.

Coronal gutta-percha was removed using size 2 special reamers for the UNIC glass fiber post (Harald Nordin sa, Chailly/Montreux, Switzerland) system supplied by the manufacturer in a low-speed handpiece to create spaces 10 mm in length, leaving 3 to 4 mm apical gutta-percha for the apical seal. Rubber stoppers were used to adjust the length. The canals were cleaned with water and dried with paper points (Maillefer-Dentsply).

## Root preparation

To standardize the dowel hole preparation, all roots were initially prepared with a size 2 UNIC drill (Harald Nordin sa) of 1.2 mm diameter mounted in a low-speed handpiece and inserted 10 mm deep within each endodontically treated canal. Prepared roots were divided into three main groups (n = 20). Group 1: control, nonweakened roots; group 2: weakened roots restored with UNIC fiber posts relined with composite resin; group 3: weakened roots restored with UNIC fiber posts.

Weakened roots of groups 2 and 3 were further prepared to simulate roots with wide canals using a size 3, 1.5 mm diameter UNIC drill mounted in a low-speed handpiece. The depth of the wide preparation was 8 mm (less than the original preparation by 2 mm) following the procedure recommended by Eglimez et al[26] to ensure a standard central position for the dowels during cementation.

While drilling dowel spaces, the low-speed handpiece was mounted in a parallelometer to ensure parallelism between the dowel preparation and the external wall of the block. The length of the preparation was guided using rubber stoppers. A new drill was used for every five preparations.

All the prepared root canals were flushed with 2 ml NaOCl solution (5.25%), and then dried with paper points (Dentsply-Maillefer). The coronal sections of all roots in the three tested groups were prepared with a UNIC counter-sinking drill for standardization. This drill is supplied with the UNIC fiber post and core system and is used to prepare the coronal section of the root to receive the prefabricated core, which will sink within the prepared area.

## Restoration of prepared roots

1. Group 1—Control (n = 20): UNIC fiber posts (Harald Nordin sa), size 2 were used to restore specimens of this group.
2. Group 2—Composite group (n = 20): the weakened roots were restored using UNIC fiber posts, size 2 relined with composite resin.

*Relining of UNIC fiber posts*: After lubricating the canal walls with glycerin gel (PURE Misr, El Monofeya, Egypt), a size 2 UNIC fiber post was painted with Shotbond (Harald Nordin sa), which was then light cured for 20 seconds. Each post was then covered with composite resin (Composan Ceram, Promedica, Neumuster, Germany) and inserted into the canal. The composite resin was light cured for 20 seconds. The relined fiber-reinforced post was removed, and the composite resin was inspected for any deficiencies. The accepted relined post was light cured for additional 20 seconds. The canal was copiously water rinsed to remove lubricant gel from the root canal.

3. Group 3—Cement group (n = 20): the weakened roots were restored using UNIC glass fiber-reinforced posts, size 2. The mismatch between the post diameter and the wide preparation was compensated for using the luting cement.

## Dowel luting procedure

A specially designed pressure jig with a 5 kg weight was machined from stainless steel to standardize load application upon the specimens during the cementation procedure. Corposit (Harald Nordin sa), a dual-curing resin cement, was used to lute the dowels following the manufacturer's recommendations as follows:

1. Shotbond, an all-in-one adhesive, which etches, primes, and bonds in one step, was applied to the canal walls using the special applicator supplied. Any excess was removed using paper points. The adhesive was then light cured.
2. Corposit cement was applied inside the canal using the special applicator supplied. The dowel was seated, and the whole specimen was mounted on the load-application device. Pressure was applied for about 60 seconds. Excess cement was removed. The cement was then light cured.

## Core application

Specimens of each group were further divided into two subgroups according to the type of core they received:

1. Subgroup a, prefabricated core (n = 10): Size 2 prefabricated UNIC core (Harald Nordin sa) was tested for accuracy of fit in the prepared countersink. Shotbond was applied using microapplicator supplied by the manufacturer. The core was cemented using Corposit cement following the same procedure used for luting the UNIC fiber post under the load applicator.
2. Subgroup b, custom-made composite core (n = 10): To standardize the shape and size of the custom-made core to resemble the size and shape of prefabricated UNIC core, a special stainless steel mold was machined. The mold consisted of two split parts that when assembled mimic the size and shape of the prefabricated core. The root face was painted with Shotbond, which was light cured. The mold was placed on each restored root after being painted with Vaseline (Johnson & Johnson, GmbH, Neuss, Germany). The countersink preparation and the mold were filled with Corposit cement. The core was light cured for 20 seconds. The mold was disassembled. The core was inspected for any defects.

## Thermocycling

All specimens were thermocycled repetitively 3000 times between water baths at 5°C and 55°C, with a dwell time of 30 seconds using a thermocycling device (Willytec, SD Mechatronik GmbH, Feldkirchen-Westerham, Germany).

**Table 1** Fracture results and comparisons for the three groups

| | Fracture (N) | | | One-way ANOVA | |
|---|---|---|---|---|---|
| Groups | Mean | SD | Range | F | *p* value |
| Control group | 567.46 | 28.28 | 536.5 to 599.3 | 730.608 | $<0.0001$[a] |
| Composite group | 408.50 | 9.08 | 394.8 to 422.53 | | |
| Cement group | 336.36 | 16.30 | 314.8 to 359.5 | | |

Tukey's test

| Control versus composite | Control versus cement | Composite versus cement |
|---|---|---|
| $p < 0.0001$[a] | $p < 0.0001$[a] | $p < 0.0001$[a] |

[a]Significant at $p \leq 0.05$.

### Fracture resistance

Five specimens from each group were selected. Each specimen was individually mounted in a custom-made jig with a 45° angulation, then secured to the lower fixed compartment of a computer-controlled materials testing machine (Model LRX-Plus; Lloyd Instruments Ltd., Fareham, UK). The specimens were statically compressed with a custom-made load applicator (steel rod with flat round end 3.4 mm diameter, placed at core tip) attached to the upper movable compartment of the machine, until fracture at a 0.5 mm/min crosshead speed with a 5 kN load cell. Data were recorded using computer software (Nexygen-MT; Lloyd Instruments).

### Type of failure

Each specimen's type of failure was examined using a 15× magnification lens. The type of failure was classified[6] into "repairable" (displacement of the dowel and core and/or cervical root fracture that would allow fabrication of a new restoration) or "irreparable" (fracture below the root cervical third, vertical or oblique fracture and horizontal fracture in the middle and apical thirds that would necessitate tooth extraction).

### Nanoleakage evaluation

Nanoleakage was qualitatively and quantitatively evaluated using an environmental scanning electron microscope (ESEM) (FEI Quanta 200 ESEM, Mérignac Cedex, France), operated with backscattered electron mode at 2000× magnification. Using the energy dispersive analytical X-ray (EDAX), the amount of silver nitrate in each specimen was measured.

#### *Specimen preparation for nanoleakage*

Five specimens from each group were removed from the epoxy resin block, painted with two layers of nail polish except circumferentially 2 mm apical to the CEJ. Each specimen was immersed in ammoniacal silver nitrate solution in a small container and wrapped with aluminum foil paper. The container was then placed in a black photo-film container to ensure total darkness for 24 hours. The specimens were then rinsed thoroughly with distilled water, and immersed in photo-developing solution for 8 hours under a fluorescent light, to reduce silver ions into metallic silver grains within voids along the bonded interface.[27] Specimens were rinsed thoroughly with distilled water and sectioned longitudinally using a slow-speed diamond blade (Isomet1000, Buehler Ltd, Lake Bluff, IL) under water cooling.

#### *Ultramorphological analysis by ESEM/EDAX*

Sectioned specimens were analyzed using ESEM (FEI Quanta 200 ESEM) at 2000× magnification. Using EDAX, the amount of silver nitrate was measured in a $170 \times 170\ \mu m^2$ area at 2000× magnification directly on the ESEM microscope monitor at three regions. Those three regions were selected from different regions of the specimens to represent different silver concentration within each specimen. The mean silver penetration values (silver wt%) were calculated. The silver nitrate uptake was expressed as a weight percentage (wt%) of the total area evaluated. SEM examination was processed blindly by three examiners independently.

### Statistical analysis

The data were collected, revised, and entered into the Statistical Package for Social Science (SPSS) version 17 (SPSS, Inc., Chicago, IL) and presented as means, standard deviations, and ranges. The three studied groups were compared with one-way ANOVA followed by Tukey's test whereas the two subgroups were compared via independent *t*-test. The confidence interval was set to 95%, and the margin of error accepted was set to 5% ($p \leq 0.05$ significant).

## Results

### Statistical analysis of fracture strength values (in N)

#### *Effect of reconstruction technique on fracture strength values*

Means, standard deviation (SD), and ranges are presented in Table 1. One-way ANOVA showed a highly significant difference between fracture strength values among different groups. Group 1 (control) showed the statistically significant highest mean fracture strength. Specimens reconstructed using composite resin (group 2) showed statistically significant lower mean fracture strength values. Specimens reconstructed using cement (group 3) showed the statistically significant lowest mean fracture strength values. Applying Tukey's test for

**Table 2** Means, standard deviations (SD), and results of comparison between prefabricated and custom-made cores in the studied groups regarding fracture strength (results in N)

| | Prefabricated | | Custom | | Independent *t*-test | |
|---|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | *t* | *p* value |
| Control group | 594.86 | 2.73 | 540.06 | 3.56 | 38.593 | <0.0001[a] |
| Composite group | 413.53 | 8.66 | 403.48 | 6.55 | 2.926 | 0.009[a] |
| Cement group | 350.75 | 7.3 | 321.97 | 6.92 | 9.045 | <0.0001[a] |

[a]Significant at $p \leq 0.05$.

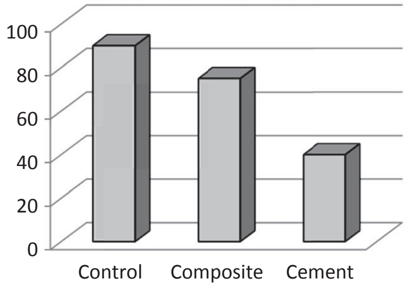


**Figure 1** Percentage of restorable failure in different groups.

pairwise comparison showed a highly significant difference when comparing tested groups with each other.

### Effect of core type on fracture strength within each group

Mean and SD values are presented in Table 2. The independent *t*-test was used to determine the effect of the type of core on the fracture strength within each group. Prefabricated cores showed statistically significant higher fracture strength values in all groups.

### Type of failure analysis

The highest percentage of restorable failure (90%) was recorded for group 1. Meanwhile, groups 2 and 3 recorded less percentage of restorable failure (75% and 40%, respectively; Fig 1).

### Results of nanoleakage

### Quantitative analysis

*Effect of reconstruction techniques on nanoleakage (silver wt%):* Means, SD, and ranges are presented in Table 3. One-way ANOVA showed a highly significant difference between amounts of silver among different tested groups. The highest silver wt% mean was recorded by specimens reconstructed using composite, group 2. Significantly less silver wt% was recorded by specimens reconstructed by luting cement, group 3. The lowest silver wt% was recorded by control specimens, group 1. Applying Tukey's test for pairwise comparison revealed no significant difference in silver wt% between the control and cement groups, while there was a high significant difference between the composite group and both control and cement groups.

*Effect of core type on nanoleakage within each group:* Within all tested groups, custom-made cores had significantly less silver wt% than prefabricated cores (Table 4). The lowest amount of silver wt% was recorded for the custom-made core of the control group. Meanwhile, the highest nanoleakage was recorded for prefabricated cores of the composite group (Table 4).

### Qualitative analysis

The observation of the photomicrographs at 2000× magnification revealed that all the specimens examined showed nanoleakage manifested by silver penetration of different patterns and different degrees. Figures 2 to 7 show ESEM photomicrographs, the element analysis table, and the EDAX spectrum of representative specimens from each group. Not all identified shiny spots are silver deposition. Shiny spots within the dowel structure are silica present in their composition (as confirmed from EDAX analysis). Dark areas between dowel and dentin correspond to the adhesive layer, which has different reflective characteristics than other substrates.

## Discussion

Excessively flared root canals have thin dentin walls, leaving them too weak to withstand normal masticatory forces and hence susceptible to fractures requiring restorative techniques that do not compromise the integrity of the remaining root structure.[28] Moreover, the restoration of these flared canals using prefabricated dowel and core systems is a challenging procedure. The discrepancy between the diameter of prefabricated dowels, which come with a standardized diameter, and the diameter of the wide canals is usually compensated for by increasing the bulk of luting cement. This results in a potentially weak area in the restoration, which may compromise the long-term prognosis.[10,28,29] In this study, the fracture resistance of nonweakened roots, serving as control, was compared to weakened roots restored with glass fiber-reinforced dowels. The discrepancy in dowel diameter was compensated for either by relining the dowel with composite resin or increasing the bulk of the luting cement.

In this study, no ferrule effect was conferred. The ferrule causes embracement of the crown on 360° of the dentinal root preparation, and it is recommended to improve the integrity of endodontically treated teeth.[30] However, in excessively flared teeth, the ferrule concept is not possible to apply because

**Table 3** Results and comparison between the three groups regarding nanoleakage

| | Nanoleakage (Ag wt%) | | | One-way ANOVA | |
|---|---|---|---|---|---|
| Groups | Mean | SD | Range | F | *p* value |
| Control group | 1.419 | 0.52 | 0.86 to 1.96 | 13.001 | <0.0001[a] |
| Composite group | 2.224 | 0.52 | 1.65 to 2.81 | | |
| Cement group | 1.648 | 0.51 | 1.1 to 2.22 | | |

Tukey's test

| Control versus composite | Control versus cement | Composite versus cement |
|---|---|---|
| $p < 0.0001$[a] | $p = 0.344$ | $p = 0.002$[a] |

[a]Significant at $p \leq 0.05$.

ferrule preparation always causes additional loss of the remaining circumferential dentine.[31]

The hypothesis that there is no significant difference in fracture strength between nonweakened roots and weakened roots reconstructed with either composite resin or cement was rejected. Table 1 shows a highly significant difference between mean values of fracture resistance of the three tested groups. None of the restoration techniques for weakened roots provided root fracture resistance values similar to those obtained with the nonweakened control group. This result is explained by the fact that the root resistance to fracture is directly related to the volume of remaining dentin.[28] Studies have shown that no material was capable of recovering root strength when compared with healthy dentin.[11,28,32,33] The findings of this study are in agreement with those of Zogheib et al,[6,28] who showed that thicker root dentin walls do significantly increase the fracture resistance of endodontically treated teeth.

The weakened roots were either rehabilitated using composite resin or luting cement. The method of reconstruction affected the fracture resistance significantly. Table 1 shows that specimens reconstructed using composite resin (group 2) showed statistically significant higher mean fracture strength values than specimens reconstructed using luting cement (group 3). These results are in accordance with other studies.[6,9] Relining fiber-reinforced dowels using composite resin increases the adaptation of the dowel to root walls and reduces the resin cement thickness. Thin layers of cement present fewer bubbles and other defects than thick ones, and voids within the material may act as crack raisers and decrease dowel retention.[3,7] The thicker cement layer present in group 3 was more inclined to present large lacunae or bubbles, reducing the cohesive strength of the resin cement.[7] In addition, the application of a large volume of cement in the root canal induces higher polymerization shrinkage that could lead to debonding.[34] Moreover, substituting the thick cement layer with composite resin, which has better mechanical and physical properties, resulted in improved fracture strength.

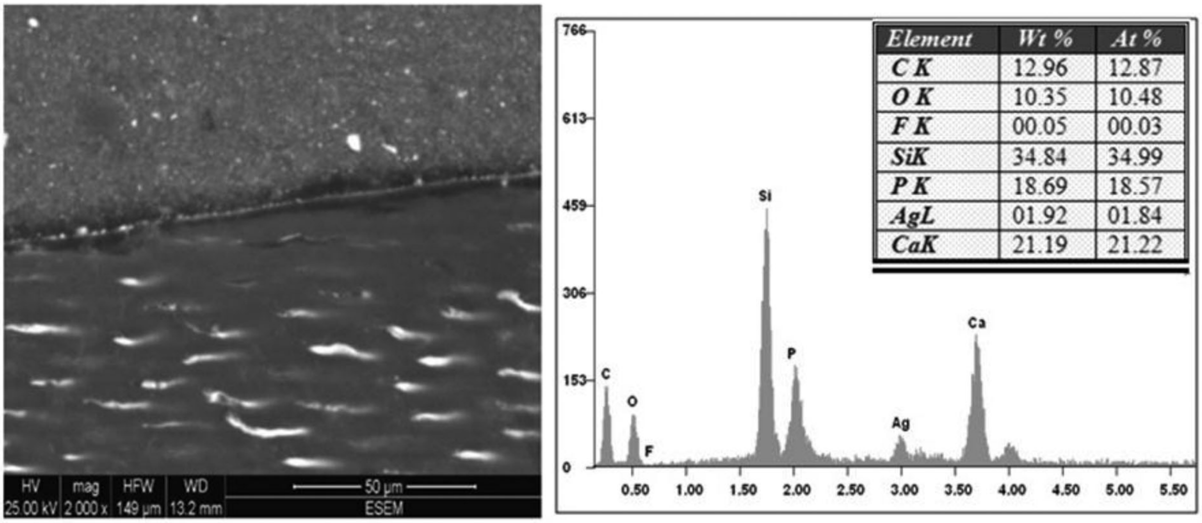
**Table 4** Results and comparison between prefabricated and custom-made cores in the studied groups regarding nanoleakage (Ag wt%)

| | Subgroups | | | | | |
|---|---|---|---|---|---|---|
| | Prefabricated | | Custom | | Independent *t*-test | |
| Groups | Mean | SD | Mean | SD | *t* | *p* value |
| Control group | 1.92 | 0.03 | 0.92 | 0.04 | 62.133 | <0.0001[a] |
| Composite group | 2.73 | 0.09 | 1.72 | 0.05 | 31.536 | <0.0001[a] |
| Cement group | 2.14 | 0.04 | 1.15 | 0.04 | 53.936 | <0.0001[a] |

[a]Significant at $p \leq 0.05$.

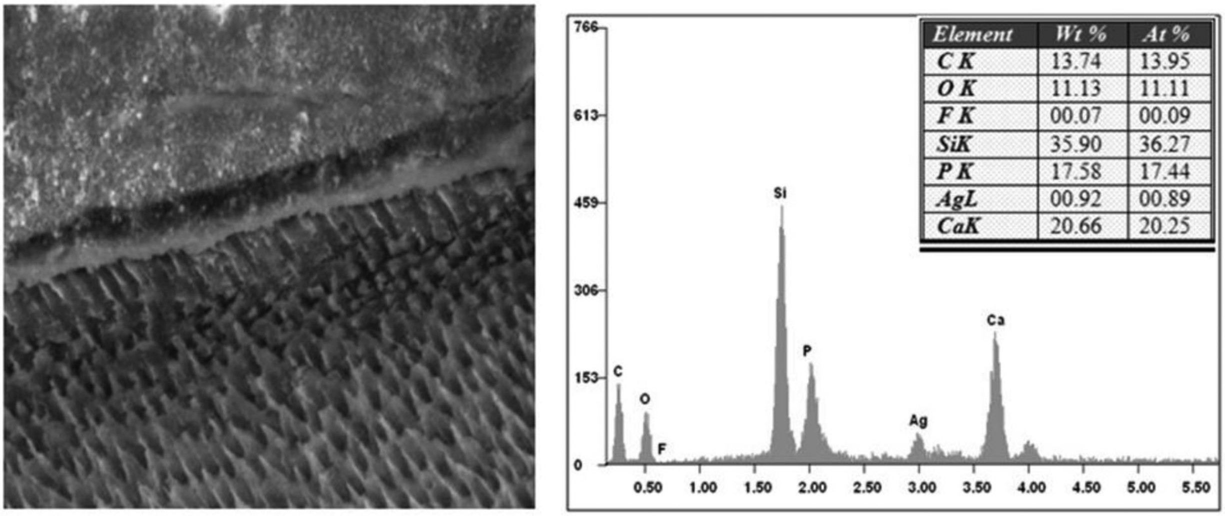
A novel dowel and core system was selected to conduct this study. The system comprises the use of a glass fiber-reinforced dowel with a prefabricated core of the same material. According to the manufacturer, the prefabricated core is adhesively luted prior to initiation of the endodontic procedure, which can be completed through the internal channel within the core structure. As a result, a temporary extracoronal restoration can be easily placed and removed during endodontic appointments, reducing the risk of reinfection. It is made of the same dowel material (i.e., glass fiber-reinforced composite); however, no previous data discussing prefabricated cores could be found. On the other hand, Corposit, a flowable composite, was used to construct the custom-made core of the same shape and dimension of the prefabricated core. The results of this study revealed that within all tested groups, the prefabricated core yielded significantly higher fracture strength values than the custom-made core (Table 2).

Core materials should exhibit good adaptation to the dowel surface. Ideally, minimal voids should be present along the interface between the dowel and the composite, as these voids may act as stress raisers and initiate mechanical failure.[35] Flowable composites, because of their low viscosity, exhibit outstanding adaptability at the dowel surface.[19,36] Therefore, these composites can potentially be used as core build-up materials; however, the flowable composites have lower filler/resin ratios than other composite build-up materials. Bayne et al[37] showed that the mechanical properties of flowable composites are generally 60% to 90% of conventional composites. On the other hand, according to the manufacturer, the UNIC prefabricated core is a glass fiber–reinforced composite material. It would be, therefore, expected that the mechanical performance of the prefabricated core would be better than that of flowable composite based on their composition. Moreover, the high resinous content of flowable composite may induce a significant contraction during polymerization, leading to the formation of a stress concentration area.



| Element | Wt % | At % |
|---|---|---|
| C K | 12.96 | 12.87 |
| O K | 10.35 | 10.48 |
| F K | 00.05 | 00.03 |
| SiK | 34.84 | 34.99 |
| P K | 18.69 | 18.57 |
| AgL | 01.92 | 01.84 |
| CaK | 21.19 | 21.22 |

**Figure 2** ESEM photomicrograph, element analysis table, and EDAX spectrum for control group/prefabricated core. Scanty spotted silver deposition pattern can be identified in the hybrid layer.



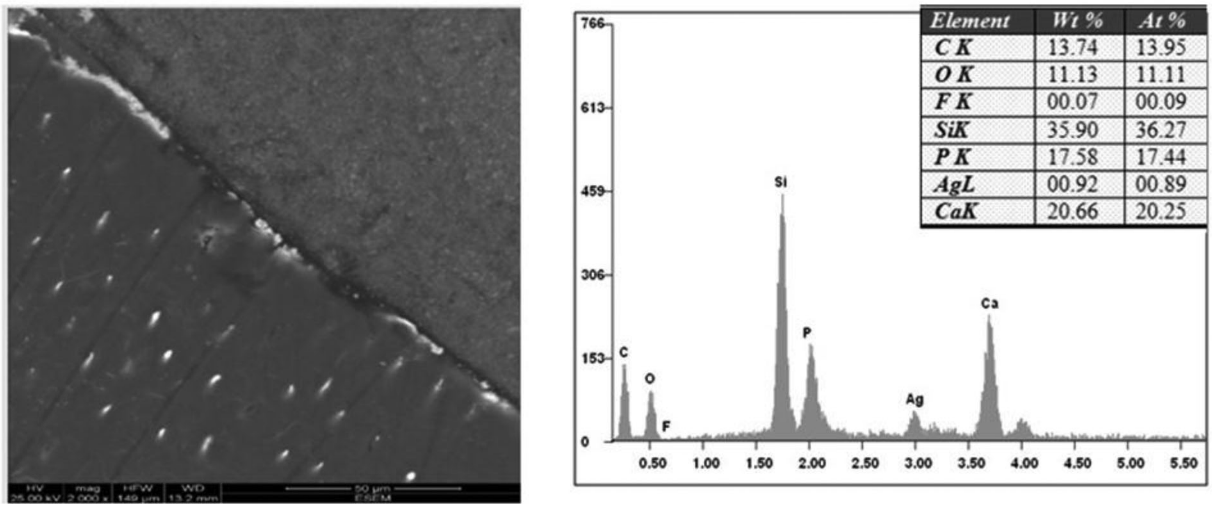
| Element | Wt % | At % |
|---|---|---|
| C K | 13.74 | 13.95 |
| O K | 11.13 | 11.11 |
| F K | 00.07 | 00.09 |
| SiK | 35.90 | 36.27 |
| P K | 17.58 | 17.44 |
| AgL | 00.92 | 00.89 |
| CaK | 20.66 | 20.25 |

**Figure 3** ESEM photomicrograph, element analysis table, and EDAX spectrum for control group/custom-made core. Few silver spots can be identified.

Analysis of the types of failure within the main groups revealed the prevalence of restorable fracture within the control group. Weakened groups (2 and 3) showed the occurrence of nonrestorable failure (25% and 60%, respectively) to a greater extent (Fig 1). The results agree with Zogheib et al[6] and Moosavi et al.[29] The modulus of elasticity of composite resins is higher than that of resin cement.[38] In other words, resin composite has physical properties similar to those of dentin, which is the main factor for root fracture resistance.[39] The thicker dentin layer in nonweakened roots provided group 1 with higher fracture strength, leading to dislodgment of the dowel and core without root fracture.

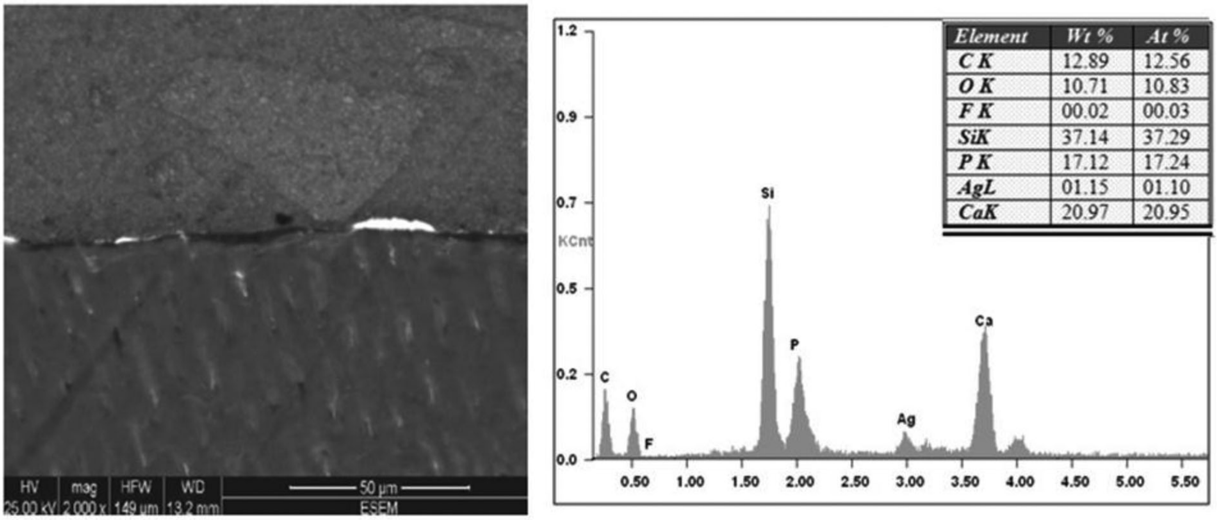
Nanoleakage is recognized as one of the factors, if not the most important one, leading to degradation of the bond to dental tissue.[40] Nanoleakage occurs laterally, through submicron porosities (estimated to be about 20 to 100 nm in width) at the base of the hybrid layer, which has not been filled with adhesive resin or which have been left poorly polymerized.[41] This demineralized but not fully hybridized dentin layer can be considered a weak point in the adhesion mechanism that could allow dentinal and oral fluid to slowly permeate the interface, and this is believed to degrade the adhesive resin.[24]

In this study, nanoleakage was qualitatively and quantitatively determined using ESEM/EDAX. This enables distinct images to be captured together with sensitive and accurate analysis.[42] ESEM provides exceptional depth of field and allows for minimal specimen preparation, allowing examination



| Element | Wt % | At % |
|---|---|---|
| C K | 13.74 | 13.95 |
| O K | 11.13 | 11.11 |
| F K | 00.07 | 00.09 |
| SiK | 35.90 | 36.27 |
| P K | 17.58 | 17.44 |
| AgL | 00.92 | 00.89 |
| CaK | 20.66 | 20.25 |

**Figure 4** ESEM photomicrograph, element analysis table, and EDAX spectrum for cement group/prefabricated core. Nanoleakage in spotted pattern can be identified.



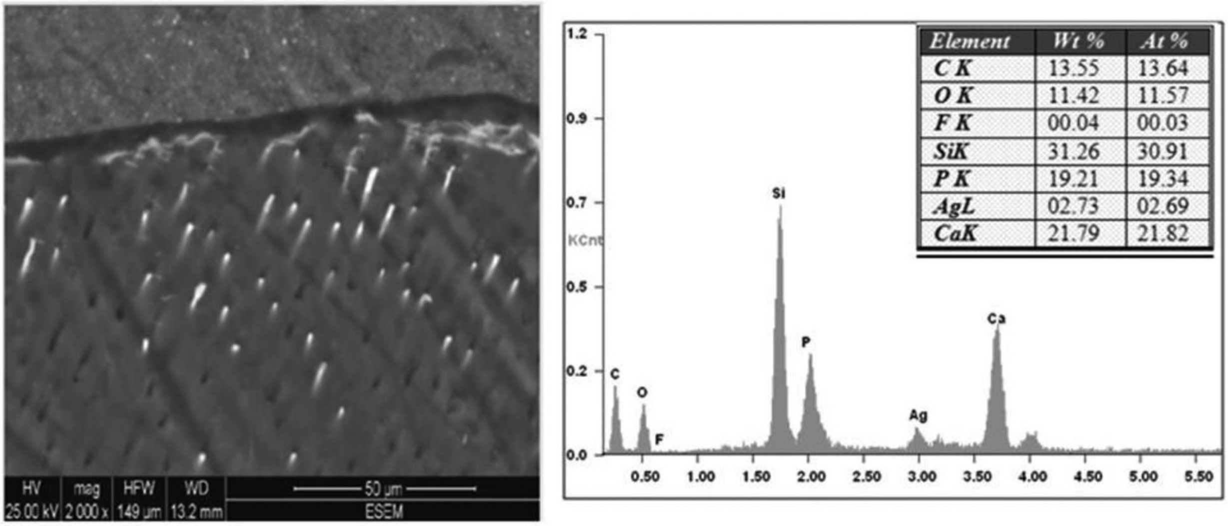
| Element | Wt % | At % |
|---|---|---|
| C K | 12.89 | 12.56 |
| O K | 10.71 | 10.83 |
| F K | 00.02 | 00.03 |
| SiK | 37.14 | 37.29 |
| P K | 17.12 | 17.24 |
| AgL | 01.15 | 01.10 |
| CaK | 20.97 | 20.95 |

**Figure 5** ESEM photomicrograph, element analysis table, and EDAX spectrum for cement group/custom-made core. Nanoleakage in spotted pattern can be identified.

of the specimens without gold or carbon coating. The concurrent EDAX analysis was carried out to identify the existence of metallic silver particles. EDAX provides accurate quantitative analysis and distribution for the various existing elements. The results of nanoleakage analyses were expressed in terms of percentages of silver deposition at three representative points.[22,24]

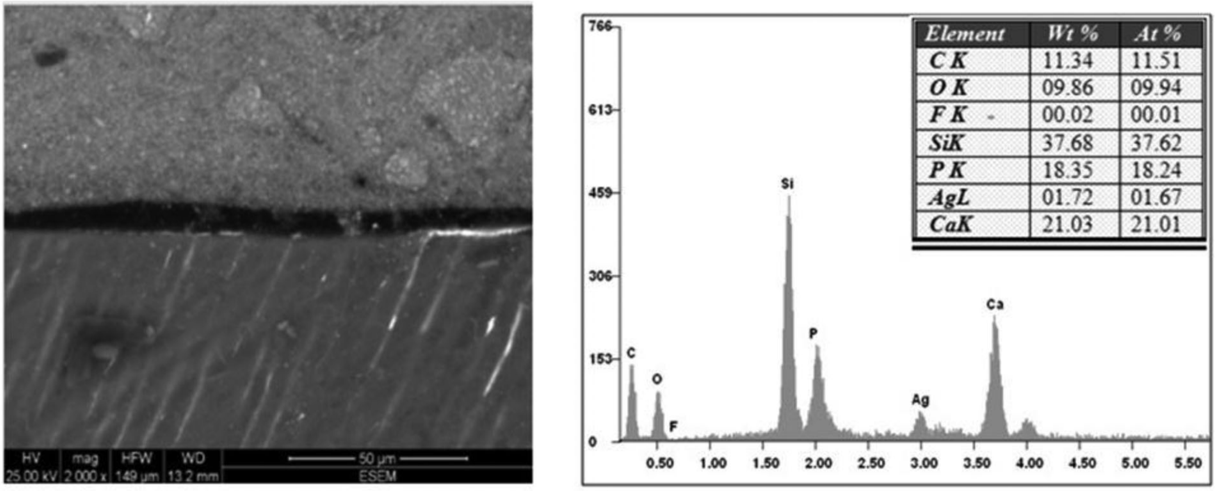
Silver nitrate staining is the most commonly used material for nanoleakage evaluation as it easily migrates within the interface zone due to its extremely small diameter molecule (0.059 nm). Moreover, silver nitrate induces an electron microscopic measurable contrast providing a sharp picture of the degree of penetration into the interface. Following its penetration, it has the potential to immobilize, which prevents further penetration during specimen preparation.[43]

All tested groups exhibited nanoleakage to different degrees (Table 3). None of the tested systems was able to provide a "leak-free" restoration. Silver uptake into hybrid and adhesive layers may be caused by imperfect resin infiltration, retained water or other solvent, poor polymerization,[44] or phase separations.[45] Water remaining in interfibrillar spaces in the course of wet bonding, may lower the degree of polymerization of the resin adhesive and/or lead to hydroxyethyl methacrylate (HEMA) hydrogel formation within the hybrid layer.[46,47] Hydrogels are highly permeable and leachable. Bitter et al[47] investigated the depth of nanoleakage of four luting agents used to lute fiber dowels. The tested agents represented self-adhesive and total-etch adhesive strategies. None of the investigated cements hermetically sealed the root canal.



| *Element* | *Wt %* | *At %* |
|---|---|---|
| *C K* | 13.55 | 13.64 |
| *O K* | 11.42 | 11.57 |
| *F K* | 00.04 | 00.03 |
| *SiK* | 31.26 | 30.91 |
| *P K* | 19.21 | 19.34 |
| *AgL* | 02.73 | 02.69 |
| *CaK* | 21.79 | 21.82 |

**Figure 6** ESEM photomicrograph, element analysis table, and EDAX spectrum for composite group/prefabricated core. Reticular nanoleakage pattern can be identified.



| *Element* | *Wt %* | *At %* |
|---|---|---|
| *C K* | 11.34 | 11.51 |
| *O K* | 09.86 | 09.94 |
| *F K* | 00.02 | 00.01 |
| *SiK* | 37.68 | 37.62 |
| *P K* | 18.35 | 18.24 |
| *AgL* | 01.72 | 01.67 |
| *CaK* | 21.03 | 21.01 |

**Figure 7** ESEM photomicrograph, element analysis table, and EDAX spectrum for composite group/custom-made core. Nanoleakage in spotted pattern can be identified.

The second null hypothesis that there is no significant difference in nanoleakage between nonweakened roots and weakened roots reconstructed with either composite resin or cement, combined with either prefabricated or custom-made core was rejected. There was a high significant difference between the three tested groups in silver wt% penetration. Weakened roots in groups 2 and 3 showed higher silver penetration means than the control group did (Table 3).

Erkut et al[48] evaluated microleakage in overflared root canals restored with four types of dowels; two prefabricated fiber-reinforced dowels and two individually shaped dowels. The lowest amount of microleakage was recorded with one type of individualized dowels, while no significant difference in microleakage could be found between prefabricated dowels with a thick luting cement layer and the second individually tailored dowel; however, in Erkut et al's study,[48] the roots were weakened using a tapered diamond bur, leaving only 1 mm of circumferential dentin around the prepared root canal. In this study the larger (with 0.3 mm circumferential difference) dowel drill was used. This slight difference in diameters between weakened and nonweakened roots could be the basis for explaining the nonsignificant difference between the cement group and control group (Table 3). Moreover, the cement group showed significantly less nanoleakage than the composite group did (Table 3). It would be expected that nanoleakage would be higher in the cement group than in the composite group, as relining the dowel with composite resin led to reduction in cement layer thickness. In theory, reducing the thickness of resin cement should result in a volumetric shrinkage reduction; however, it is not clear if polymerization shrinkage stress along cavity walls is also reduced due to the reduction in resin layer thickness in a low compliance environment.[13] A previous study showed that polymerization contraction stress in thin resin composite films increases, while the layer thickness of the composite decreases.[49] Therefore, it may be assumed that high contraction stresses in a thin luting resin layer surrounding relined dowels may be expected during polymerization.

In addition, relined dowels are considered a type of tertiary monoblock, where three interfaces are identified. The introduction of a tertiary interface is problematic in that gaps were found to be present between the dowels and the relining composite.[7] These gaps may act as stress raisers and passage for leakage. On the other hand, the cement group is a binary monoblock, where two interfaces are identified. An increased number of interfaces will increase the possibility of leakage.[13]

The qualitative assessment of the nanoleakage pattern revealed the prevalence of the spotted nanoleakage pattern in the three groups (Figs 2–7). Reticular nanoleakage was identified only in the composite/prefabricated group (Fig 6).

The spotted pattern of nanoleakage expression represents regional hydrophilic phases within the adhesive that are more prone to water sorption. It represents potentially permeable regions in the adhesive and hybrid layers that result from the interaction of the basic silver ions with acidic/hydrophilic resin components.[50] Meanwhile, the occurrence of the reticular mode of nanoleakage represents areas in which water was incompletely removed from the resin/dentin interfaces. Residual water within the adhesive may lead to areas of incomplete polymerization of the adhesive or sequestrations of more hydrophilic oligomers in these specific areas.[50,51]

This in vitro study presented limitations common to tests conducted on human teeth, such as specific dimensions, static compressive load, and fixed angulations. Clinical extrapolation of the results must be done judiciously and prudently, since it is not possible to simulate all the conditions of the oral environment. Another limitation to this study is the absence of an extracoronal restoration; however, this study presented the simulation of a worst-case scenario (i.e., a deficient coronal restoration that allowed bacteria, enzyme, and fluid penetration into the root canal). Although none of the studied combinations provided a total seal against leakage, the presence of an extracoronal restoration may change the situation. The concept of a prefabricated core, although appealing, should be thoroughly investigated.

## Conclusions

Within the limitations of this study and for the tested materials, the following could be concluded:

1. Dentin thickness is a decisive factor in determining the fracture strength of endodontically treated teeth.
2. Individualizing glass fiber-reinforced dowels using composite resin in wide root canals is recommended over using thick luting cement layer regarding fracture strength.
3. Using a prefabricated core in the restoration of endodontically treated teeth seems a promising technique, but needs further investigation.
4. Nanoleakage occurs to variable degrees in adhesively luted glass fiber-reinforced dowels, especially in wide canals.

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