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Fracture resistance of endodontically treated teeth without ferrule using a novel H-shaped short post

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Objective: To evaluate the fracture resistance and failure types of modified H-designed intradental short retention preparation for computer-aided design/computer-assisted manufacture (CAD/CAM) restorations, in cases where no ferrule is possible. **Method and Materials:** A combined finite element analysis and in vitro testing was employed. Forty extracted single-rooted premolars were selected and prepared for the following four groups (n = 10 per group): Group A, H-post preparation restored with glass-ceramic crowns; group B, H-post preparation restored with lithium disilicate crowns; group C, endocrowns (negative control group); and group D, 2-mm ferrule preparation and restoration with fiber posts (positive control). After cementation, specimens were loaded to fracture (1 mm/min) in a universal testing machine. The data were analyzed using Kolmogorov-Smirnov, Shapiro-Wilk test, one-way ANOVA, followed by post-hoc Scheffé test and chi-square test. **Results:** The H-post group restored with lithium disilicate crowns (group B) presented higher fracture resistance compared to the H-post group with glass-ceramic crowns (group A) and the endocrowns (group C). Among the failure analysis, only specimens of group C were all repairable after fracture load test, while the specimens of remaining groups A, B, and D accounted for 90%, 70%, and 50% repairable fracture modes, respectively. **Conclusion:** The modification of the short intracoronal restoration anchorage profile may be a valid concept to improve the retention and fracture resistance, given that the materials are adjusted for this purpose in terms of mechanical resistance and internal adaptation. Numerical evaluations and future in vitro studies may help to select the best designs and materials. *(Quintessence Int 2015;46:97–109; doi: 10.3290/j.qi.a32634)*

Key words: bonding, CAD/CAM, ceramic, failure types, finite element analysis, fracture resistance

Restoration of endodontically treated teeth represents a major clinical challenge in contemporary dentistry. Conventionally, severely compromised teeth are restored using post-retained restorations, with the post providing retention of the core and transferring the load from the crown onto the remaining root structure.

Although the use of posts is a very traditional dental procedure that was recommended more than 100 years ago to retain crowns,[1] the basics have remained virtually unchanged: a cylindrical or tapered post that should extend as much as possible within the root canal but with a length no less than the height of the

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crown, so that the arms of effective lever are at least equal. Over time, the fundamental design of the posts has remained unchanged, with most of the improvements involving the material from which the post is made. The biomechanical behavior of the posts has been intensively investigated both in vivo and in vitro but as yet there is no consensus about the advantages of any given system.[2,3] Commonly, the behavior of a certain post system is either extracted from existing clinical data or inferred from laboratory studies. The in vitro testing often tests the resistance of the restoration, ie the maximum load that the post-restored tooth can withstand before catastrophic failure. As such, there is a large amount of quantitative information regarding the overall fracture resistance of teeth restored with various posts systems, but there is little qualitative information regarding the events involved in the failure of the restoration, and the features of design that may prevent it. Preservation of tooth tissue, length of the post, presence of a ferrule effect, and adhesion are regarded as the most effective conditions for long-term success of post-endodontic restorations.[4] Recent work indicates that a partial ferrule is superior to the absence of a ferrule for the fracture resistance of the restored tooth.[5] However, in the case of severely damaged teeth there is little remaining tooth structure for the ferrule to be established, and therefore the clinical serviceability of such teeth may be compromised. In such cases additional clinical procedures such as crown lengthening and orthodontic extrusion have been suggested to provide additional coronal dentin.[6] Such clinical difficulties leave open the need for an alternative and practical solution to increase the mechanical resistance in severely compromised endodontically treated teeth.

This article presents a new concept of a short post design, which could increase the fracture resistance of single-rooted compromised teeth whose remaining tooth structure does not allow for a ferrule to be part of the preparation. Two experimental observations underpin this work. First, it has been shown that anchorage of the crown only within the pulp chamber (ie, endocrown) provides satisfactory clinical retention.[6] Second, the previous simulation showed that the interfacial displacements under loading between the crown, post, and root are important in the mechanism of failure and can be used to infer the mechanical strength of the restored tooth.[7,8]

To test this concept a two-part study was designed. First, finite element analysis (FEA) was used to analyze the interfacial displacements between the post and dentin under loading. This was followed by testing the strength of the restoration in vitro, in which the fracture resistance of teeth restored with H posts was compared to that of the teeth restored with other current methods.

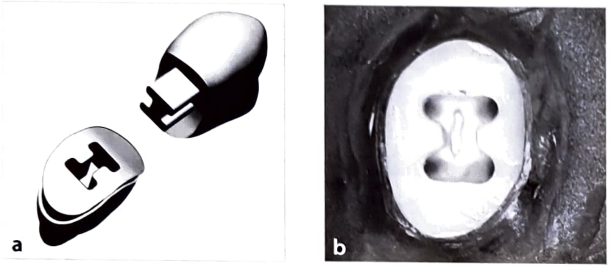
METHOD AND MATERIALS

H-post design

The contour of the proposed post was similar to a structural H-shape beam with its mid-rib (web) oriented along the buccolingual axis of the tooth traversing the pulp chamber and the two parallel segments of the H (flanges) engaging the dentin buccal and lingual sides of the pulp chamber (Fig 1). This cross-section allows for superior rigidity of the post and better engagement of the remaining radicular dentin, which results in smaller strains across the interfaces of the components of the restoration hence increasing the fracture resistance of the restoration.

Numerical analysis

The FEA used a single tooth model derived from an intact adult human maxillary first premolar free of cracks and fractures, extracted for periodontal reasons.[9] The tooth was digitized using micro-computed tomography (microCT; SkyScan) and a solid surface model was subsequently generated in a CAD program (Rhinoceros 3D for Windows, McNeel and Associates). The process for reconstruction and surface generation was similar to that used previously[7] and started from a stack of 1,300 slices from which the initial triangular meshes of the assembly were generated. The meshes were subsequently converted to NURBS (non-uniform rational B-splines) defining the matching bodies: root, post-and-core, and crown.



Figs 1a and 1b H-post design. *(a)* 3D model of the root with the preparation for the H post, the mono-block H post, the core, and the crown. *(b)* The preparation on a natural tooth.

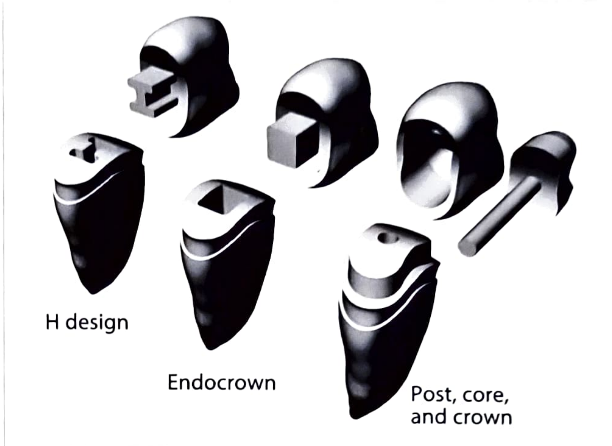


Fig 2 Disassembled view of the 3D models considered for analysis.

To account for the periodontal ligament, the digital model was completed by adding a material layer of 0.3-mm uniform thickness around the root, which stopped 2 mm below the cementoenamel junction (CEJ). The intra-alveolar portion was contained in a fixture to simulate the alveolar support.

The resulting solid model was digitally fitted with a post-retained crown for the following cases: H-post design (groups A and B), endocrown (group C), and a 2-mm circumferential ferrule preparation with a 2-mm diameter parallel sided post which extended over half of the length of the root (group D; Fig 2).

The intraradicular extension of the H post and the endocrown slot preparation was limited to 2.5 mm to account for the limitations of manual preparation and the scanning capabilities of the CAD/CAM systems. Both the H post and the endocrown were considered to be forming a common piece with the crown so that it simulates the milling of the restoration from a single block of ceramic. A minimum of 1 mm of residual dentin was preserved between the intraradicular preparation and the root margin for the H post and the endocrown.

All three models were imported into a general purpose FE software (SolidWorks Simulation, Dassault Systemes) and contact linear analyses were setup for each case. To allow for the investigation of the interfacial displacements, the formulation of the contacts between the restoration and tooth allowed for the components to move away from each other, but they preserved the physical requirement of not penetrating each other (frictionless, unbonded). All the other contacts of the assembly were considered as bonded, which means that the interfaces will not separate under loading. This method has been previously employed to study the interfacial behavior of restored teeth.[10] Incorporating non-bonded contacts into analysis allows measurement of the relative displacements of the assembly components. This in turn can be used to infer the amount of energy that will be transferred to the interface holding the components together (ie, the luting agent). In the present study, by comparing the size of the gap occurring between the crown and dentin on the palatal aspect of all four cases, we can compare the amount of mechanical energy transferred to the luting agent as tensile forces, and which act to disassemble the restoration, being in effect an indication of the strength of the assembled restorations.

For all cases, 0.3-mm linear elements were used on the unbonded contacts, and 0.9-mm linear elements for the rest of the model. All cases were loaded with a force of 100 N on the palatal aspect oriented at 30 degrees to the long axis of the tooth and identically restrained on the base of their supports.

All the materials were assumed as linear elastic. The root was considered as made out of dentin with an elastic modulus (E) of 15 GPa, and the ligament was simulated in a rubbery material with an E of 12 MPa.[10] The H post and the endocrown were considered as monolithic units milled from glass-ceramic material with an E of 65 GPa.

For the ferrule case, the crown was considered as milled from the same glass-ceramic material, the posts was considered to be made of fiber-reinforced composite with an E of 24 GPa,[11] and the core as manufactured from hybrid composite with an E of 11 GPa. These material properties were chosen to reflect the experimental setup, which will be used for the in vitro testing.

After running the analyses, the resulting displacements were measured as maximum displacement of the crown measured at the tip of the buccal cusp, the resulting displacement of the palatal margin of the crown, and the resulting displacement of the palatal dentin. All the displacements were collected as nodal values and represent the sum of the component displacements (x, y, z). The size of the palatal gap was determined by subtracting the displacement of the dentin from the displacement of the crown.

Furthermore, the principal tensile stresses produced in the restoration were also analyzed to identify the location of critical stresses in the restored tooth.

Evaluation of the fracture resistance

Forty extracted maxillary human premolars were selected, cleaned, and stored in 0.5% chloramine T (Sigma-Aldrich Laborchemikalien) at room temperature for a maximum of 7 days. Afterwards, they were stored in distilled water for a maximum of 6 months at 5°C until the experiments. All teeth had one radiographically visible root canal, exhibited no visible signs of cracks, fractures, or root caries, and showed comparable diameters. Crowns were removed at the level of the CEJ, leaving roots of 10 ± 1 mm long. In ten teeth, crowns were removed 2 mm above the CEJ to allow additional space coronally for the circular preparation of a ferrule.

Teeth were root canal treated using Profile 0.4 (Dentsply). The working length was assessed with digital X-rays (Digora). The master apical file was no. 35. No step-back procedure was performed. After each file, the canal was rinsed with sodium hypochlorite (3% w/v). After root canal preparation, the canals were dried with paper points no. 35 (Dr Wild & Co) and obturated with a single-cone technique using gutta-percha points no. 35 (Roeko). To ensure complete setting of the provisional material, all teeth were stored in a humidity chamber for 24 hours.

All roots were then covered with an air-thinned 0.2-mm layer of polyvinylsiloxane (President light, surface activated) to simulate a periodontal ligament. They were then centrally mounted with chemically cured resin (Paladur, Heraeus Kulzer) with a centering device (PPK). The distance between the CEJ and the resin was 2 mm.

Subsequently, all preparation steps were performed under fixation of the carriers in a parallelometer (PFG 100, Cendres & Metaux) and the roots were randomly assigned to one of the following four groups (N = 10 per group):

- Groups A and B: the H-post
- Group C: endocrown
- Group D: control where the teeth were prepared with a 2-mm ferrule and restored with fiber posts (Figs 3 and 4).

- **Groups A and B (H-post):** Teeth were prepared to receive a H-shape post with its web (3.4 mm) oriented along the bucco-oral axis of the tooth traversing the pulp chamber. The two parallel flanges of the H aimed to engage the dentin buccally and orally and were individually adapted to leave a minimal residual lateral dentin thickness of at least 1 mm. The depth of the cavity was 2.5 mm and the outline of the preparation was rounded to prevent stress concentrations on sharp corners as well as facilitating the milling (Figs 1 and 2). The only difference between the groups A and B was the material out of which the restoration was milled: glass-ceramic for group A and lithium disilicate for

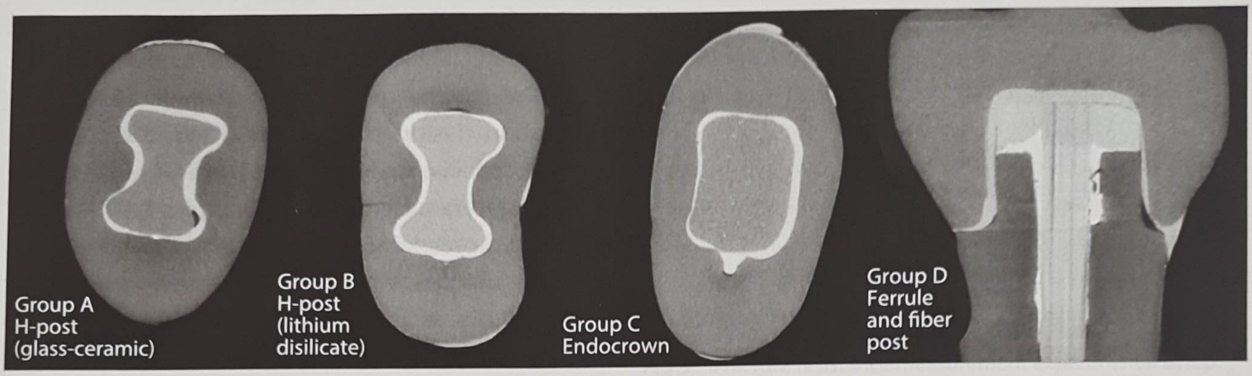


Fig 3 MicroCT sections illustrating the four groups.

Figs 4a to 4l Clinical situation of the three different preparations: Post and core with ferrule (left column, *a, d, g, j*), H post (middle column, *b, e, h, k*), and endocrown (right column, *c, f, i, l*). From top to bottom: Clinical situation under rubber dam (occlusal view, *a* to *c*; lateral view, *d* to *f*); Virtual crown design (crown in place, *g* to *i*; milling preview, *j* to *l*).

group B. Both materials were included in the study based on the FEA to avoid the premature fracture of the ceramic, and so that the geometry of the H-design could be isolated.

- **Group C (endocrown, negative control group):** The teeth were prepared with a round inlay cavity of 2.5-mm depth, which was limited to 1-mm residual marginal dentin thickness.
- **Group D (post and core, positive control group):** 6-mm deep preparations for a glass fiber post (Endo Easy Efficient Yellow, VDW) were made in a slow-speed contra-angle handpiece. The canals were rinsed with tap water and an adhesive system (Adhese, Ivoclar Vivadent) was applied according to the manufacturer's instructions. A self-curing resin luting material (Luxacore, DMG) was applied to the surface and brought into the prepared root canal with a no. 25 lentulo spiral (Maillefer). The glass fiber post was alumina powder air-abraded (50 µm; Benzer Dental) at 0.1 MPa pressure (Microetcher, Danville Engineering), silanized (Monobond-S, Ivoclar Vivadent) for 60 seconds, covered with a thin film of bond, and inserted into the soft luting-composite-filled root canal. Excess material was removed with a probe before polymerization from the buccal and oral surfaces with a light gun (Bluephase LED G2, Ivoclar Vivadent) for 60 seconds each. Filtek Supreme (3M ESPE) was then used immediately after post cementation as a composite material to build up a core, which was co-polymerized from the buccal and oral surfaces using the same polymerization device for 40 seconds each at 1200 mW/cm^2. The core was prepared and finished in the parallelometer with tapered diamond burs under water-cooling. The ferrule height was 2 mm and the shoulder width was 0.8 mm. A minimal ferrule thickness of at least 1 mm was maintained. The core build-up was standardized to a height of 5.5 mm in the fissure and 6.5 mm in the cusp region (distances measured from the shoulder).

The preparation surface area of the preparations of all groups was scanned (Cerec AC BlueCam, Sirona) after application of a thin coating with scanspray (Scan'Spray, Dentaco), and measured as described earlier.[12] The crowns' geometry was standardized using correlation design mode (CEREC SW 3.80). Subsequently, specimens of groups A, C, and D were restored with glass-ceramic crowns (IPS Empress CAD Multi LT A2/I12, Empress CAD HT B3/I12, Ivoclar Vivadent), whereas samples of group B were restored using a lithium disilicate ceramic (e.max CAD MO2/C14, Ivoclar Vivadent). Occlusal thickness in the main fissure was set to 1 mm and the luting space was set at 90 µm.

All root specimens were cleaned with water, toothpaste (Signal AntiCaries, Elida Fabergé) and slowly rotating nylon brushes (Kerr). Preparations were carefully refinished with 25-mm finishing diamond burs under water-cooling. Syntac Primer was applied for 15 seconds. After another 15 seconds, the primer was slightly dried. Syntac Adhesive was applied and slightly dried after 20 seconds' penetration time. Heliobond was then applied and carefully thinned with air after a penetration time of at least 40 seconds. Care was taken to leave a very thin but intact film and to avoid any pooling, which would lead to an ill-fitting crown. The bonding agent was then polymerized occlusally for 60 seconds (Bluephase LED G2, Ivoclar Vivadent).

The glass-ceramic crowns of groups A, C, and D were etched with hydrofluoric acid for 60 seconds (Vita Ceramics Etch, Vita Zahnfabrik) and water-spray was applied for 40 seconds to avoid precipitation on the surface. The internal crown aspects were then silanized (Monobond-S, Ivoclar Vivadent). After 60 seconds, the solvent was air-dried and the surface was covered with a thin film of Heliobond (Ivoclar Vivadent), which was not polymerized separately. A restorative composite (Filtek Supreme, 3M ESPE) was filled into the crowns and carefully adapted to all surfaces/walls. The crowns were placed on their respective prepared teeth and brought to their end positions with ultrasound (SP Tip and Piezo-Master 400, EMS). The surplus composite was removed with a probe and after a final ultrasonic action, the composite was polymerized through the crown from all five aspects for 60 seconds each (Bluephase LED G2, Ivoclar Vivadent). The small amount of polymerized surplus composite was removed and the surface polished with Soflex discs of descending grain size at ×10 magnification. Specimens were stored for 24 hours in water at room temperature.

The lithium disilicate crowns were additionally crystallized using a Programat XP1 (Ivoclar Vivadent) oven for 5 minutes at 750°C plus 10 minutes at 850°C after the milling process. The prospective bonding surface was then air-abraded with 50 µm Al_2O_3 and a universal, single-component silane (Monobond Plus, Ivoclar Vivadent) was applied for 60 seconds.

All specimens were then placed in a custom-made carrier with an inclination of 30 degrees, and loaded in a universal testing machine (Zwick Z010, Zwick/Roell) with a 5-mm steel sphere and a cross-head speed of 1 mm/min until the first major load drop. A 0.5-mm piece of tin foil (Dentaurum) between the steel sphere and crown allowed a more equal load distribution and avoided loading peaks on the ceramic crown surface (Fig 5).

After failure, the fragments were analyzed for the failure mode: crown fracture, crown fracture and post-fracture, tooth fracture that might clinically allow a new crown placement, and tooth/root fracture that would necessitate tooth extraction.

Statistical analysis

Approximate normality of data distribution was tested using Kolmogorov-Smirnov and Shapiro-Wilk tests. Descriptive statistics for bond area and fracture resistance were calculated. One-way ANOVA was used for the analysis of bond area and fracture resistance, followed by post-hoc Scheffé test to evaluate the statistical differences between the test groups.

After fracture load test, the failure types were classified, the relative frequencies of failure types were calculated[13] and evaluated using chi-square analysis (SPSS, Version 19). In all tests, P values smaller than 5% were considered as statistically significant.

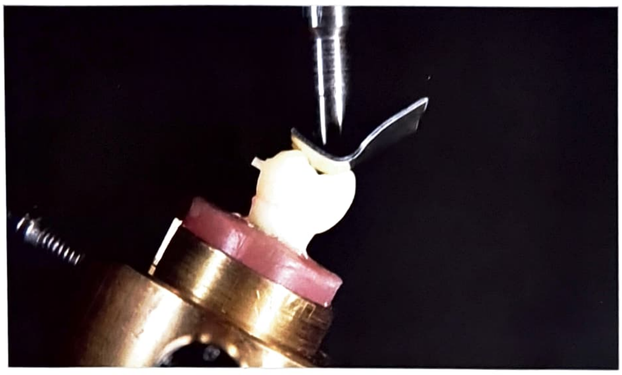


Fig 5 Fracture resistance measurement experimental setup.

RESULTS

Numerical analysis

The displacement data in Table 1 show that the size of the palatal gap is similar for the H-post design and the ferruled restoration. In contrast, the endocrown will produce a palatal gap of about twice the size.

Figure 6 shows a comparative view of the tensile stress profiles in the remaining radicular dentin under a 100 N load. The stress analysis of the H post shows that the maximum tensile stresses in the remaining dentin are within a 25 to 30 MPa range, concentrated on the proximal extremities of the flanges. These areas are limited in size, isolated, and surrounded by lower stress fields. On the other hand, the H post shows the tensile stresses peaking at the junction between the palatal flange and the core are in the range of 33 to 35 MPa.

The maximum tensile stresses in the preparation for the endocrown are in the 55 to 60 MPa range and concentrated around the mesial corners of the radicular slot preparation. The areas of maximum stress are more extensive and the stress field distribution in the remaining dentin is higher compared to the H design.

The composite post preparation shows the lowest stresses, in the range of 15 to 20 MPa located on its mesial aspect. Also, the stress field in the surrounding dentin is rather small.

Bond area

The dimensions of the teeth measured at the prospective finish line accounted at the buccolingual and

Table 1 Determined displacements in the tested models (µm) and a resultant displacement plot showing the palatal gap formation in the tooth restored with a H post (deformation scale ×10)

	H post	Endocrown	Composite post and ferrule
Crown displacement	57	73	58
Dentin displacement	44	43	45
Palatal gap	13	30	13

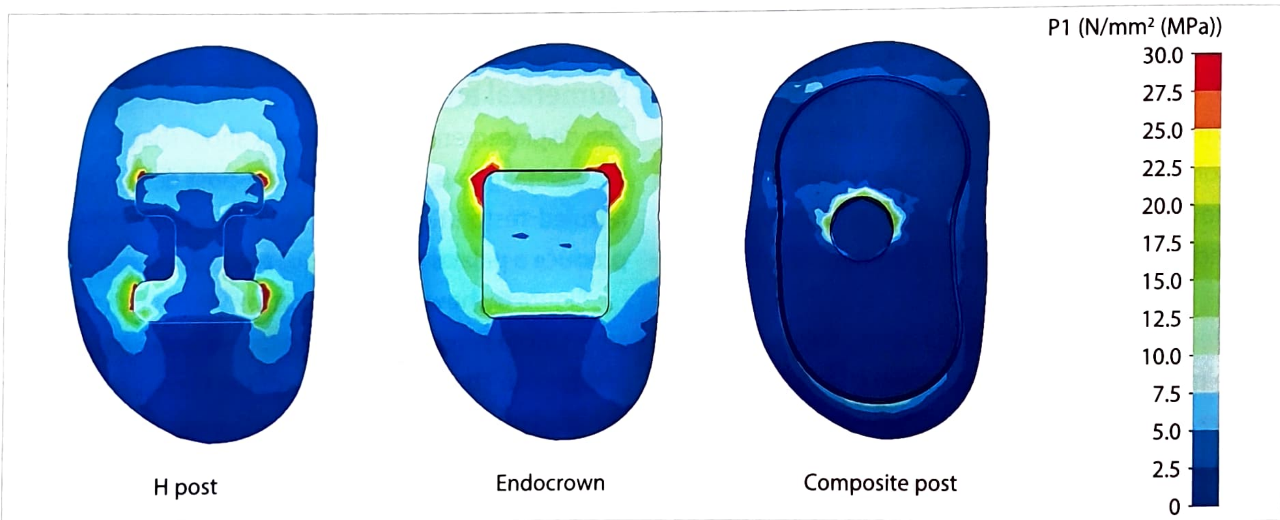


Fig 6 Tensile stress plots of the preparation and the H post.

mesiodistal aspect for 7.3 ± 0.6 mm and 4.7 ± 0.3 mm, respectively. Table 2 provides descriptive statistics (mean ± standard deviation [SD], 95% confidence interval [CI]) and the results of one-way ANOVA with Scheffé post-hoc test of the scanned bonded area for CAD/CAM ceramic crowns. Differences of bond area were observed depending of preparation type ($P = .002$). Test group D showed significantly greater bonding compared to groups B and C.

Fracture resistance

Kolmogorov-Smirnov and Shapiro-Wilk tests indicated that the fracture resistance data were normally distributed (100%). Consequently, parametric statistical analyses were applied. One-way ANOVA analysis showed for fracture resistance values statistical differences between the tested groups ($P = .001$) (Table 3, Fig 7). Group B presented significantly higher fracture resistance values compared to groups A and C. No significant differences between the remaining groups were found.

Failure analysis

Typical aspects of failure are illustrated in Fig 8. Table 4 presents the relative frequencies of clinical repairable failure types at 95% CI. Significant differences were found in the frequency of clinical repairable failure type between the test groups ($P < .001$, chi-square test). Only specimens of group C were all repairable after fracture, while the specimens of groups A, B, and D accounted for 90%, 70%, and 50% repairable fracture modes, respectively.

Table 2 Descriptive statistics (mean ± SD, 95% CI) and the results of one-way ANOVA with Scheffé post-hoc test of the scanned bond area for CAD/CAM ceramic crowns

Test group	Mean ± SD (mm²)	95% CI (mm²)
A	60.7 ± 8[AB]	55.1–66.3
B	57.0 ± 7[A]	51.5–62.4
C	55.0 ± 5[A]	51.2–58.8
D	67.8 ± 7[B]	62.0–62.4

[AB], letters reflect the results from one-way ANOVA: different letters represent a significant post-hoc Scheffé test between the levels of the test group factor.

Table 3 Descriptive statistics (mean ± SD, 95% CI) and the results of one-way ANOVA with Scheffé post-hoc test of fracture resistance (N)

Test group	Mean ± SD	95% CI	Min.	Median	Max.
A	547 ± 232[A]	381–713	148	654	807
B	1,044 ± 501[B]	685–1,402	305	1,135	1,632
C	592.4 ± 147[A]	487–697	375	577	800
D	890 ± 125[AB]	800–979	734	912	1,103

[AB], letters reflect the results from one-way ANOVA: different letters represent a significant post-hoc Scheffé test between the levels of the test group factor.

Table 4 Relative frequencies with 95% CIs of clinical repairable failure types after fracture load measurement

Test group	Relative frequency (%)	95% CI
A	90	55–100
B	70	6–66
C	100	69–100
D	50	18–82

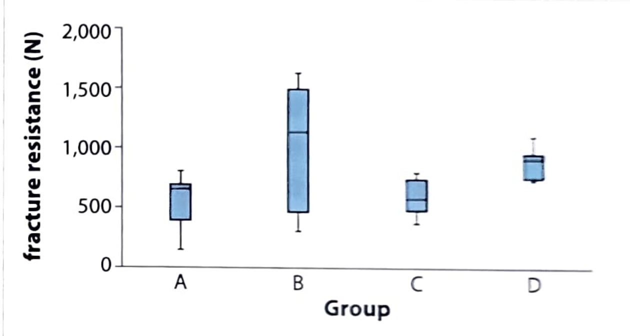
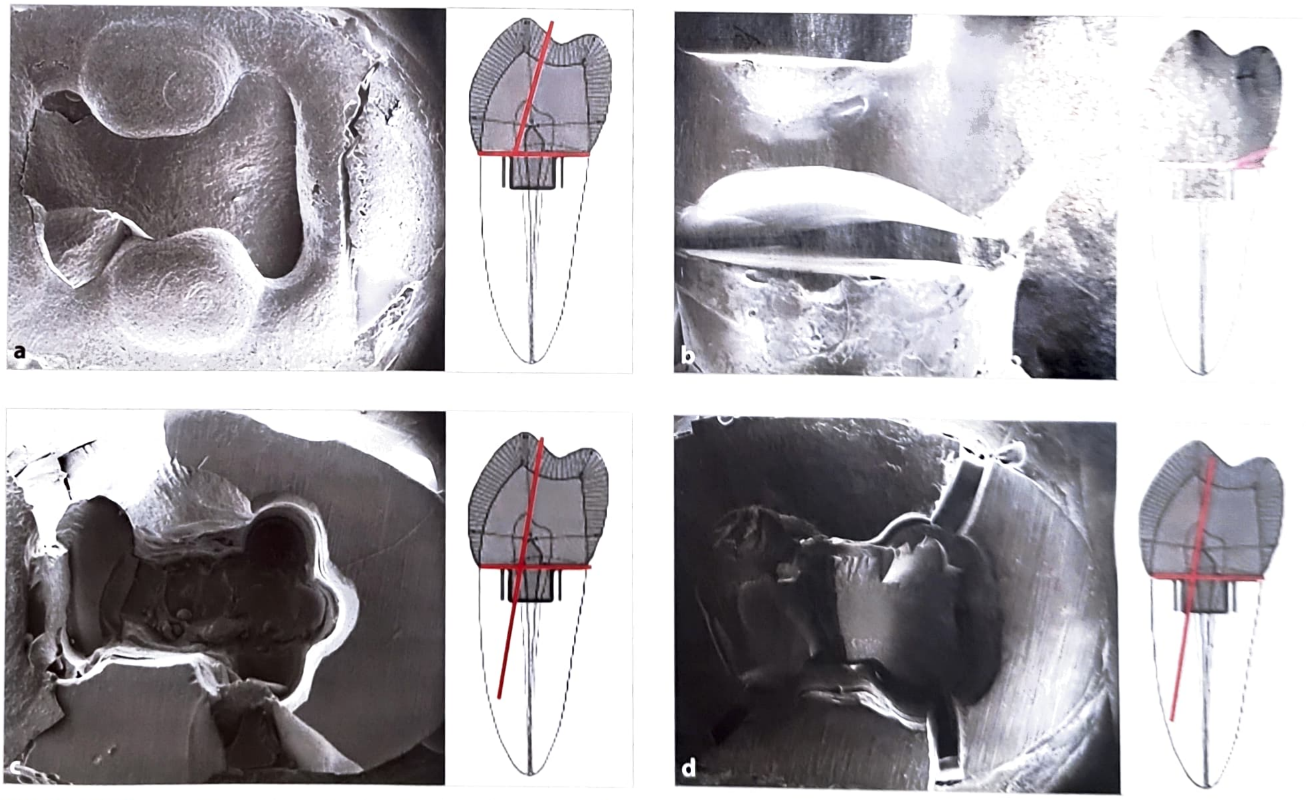


Fig 7 Boxplot of the fracture resistance of all tested groups.



Figs 8a to 8d Representative SEM images showing repairable (*a and b*) and irreparable failures (*c and d*) of the H post groups.

DISCUSSION

In this study, the fracture resistance and failure types of modified H-designed intradental retention preparations for CAD/CAM restorations were analyzed in simulated cases without ferrule. The design of the novel post is aimed at minimizing the interfacial displacements by engaging the dentin while it keeps its intraradicular apical extension limited. To test the concept, a combined approach was employed, using virtual prototyping, FEA, and in vitro testing to assess the biomechanical behavior of the new post design.

The results show that the new geometry of the post combined with a higher strength ceramic is capable of delivering higher fracture strength when compared to the other groups, considering its median and maximum values of 1,135 N and 1,632 N, respectively. Therefore, the hypothesis was accepted.

In the present study FEA was used to test the underpinning concept and to explore the intimate biomechanical behavior. In recent years, numerical simulation has developed significantly and current systems are capable of not only indicating the stress profiles but also dynamically predicting and simulating crack initiation and propagation through the structure. Such advanced numerical simulations are extremely computationally intensive and require special mathematical formulations that capture the failure mode of each of the materials considered. However, for this study a rather "conventional" numerical analysis was employed in which it was not simulation of crack initiation and growth that were used, but rather the interfacial displacement between the different components of the restoration that were used to infer the amount of energy which will act to separate the assembly. Interfaces are largely accepted as being *locus minoris resistentiae* in all mechanical assemblies, and as such, examining the interfacial events under loading provides a good insight in load transfer and overload, and indicates the likely areas of failure initiation. By comparing the FEA results with the laboratory experiment it was possible to confirm the predictive capability of this approach.

There is a very good agreement between the calculated size of the marginal gap using FEA and the fracture resistance of the groups tested. Furthermore, the location of the peak tensile stresses as determined by FEA is in agreement with the location of cracks and fractures observed on fractured specimens. In the present analysis a 100 N load was used, which generated a dentin stress of about 30 MPa. Considering that the ultimate tensile strength of the dentin can exceed 140 MPa,[14] and of the glass-ceramic (Empress CAD) 160 MPa, FEA predicts critical stress levels at a load of circa 500 N, which could cause dentin or ceramic fracture. Figure 7 shows that the failures in groups A and C (dentin and glass-ceramic) are clustered around the same loading range. However, the experimental values were higher, which can be explained by the effect of the bonding, which was not captured by the FEA. In vivo, because of the consolidation of the bonding condition and of the increased fracture toughness of the dentin, the ceramic component has a higher chance of catastrophic failure. These facts explain the rate of repairable failures of 90% and 100% in groups A and C respectively.

Once a tougher ceramic is introduced, as was the case for group B, the strength of the restoration increases and so does the likelihood of an irreparable failure, as the dentin will fracture ahead of the ceramic. Fracture analysis also revealed that the H post behaves as predicted, interlocking the radicular dentin between its flanges (Fig 7) and this mechanical behavior is associated with the highest fracture strength. Upon loading, the post will tend to displace bucally but this motion will be transmitted to the dentin engaged between the flanges, effectively keeping the root close to the post, and this active engagement results in a smaller interfacial separation (Table 1). An interesting observation is that the scanning electron microscope (SEM) images show aspects typical of adhesive failure, eg Figs 8d and 8e. However, it is unclear if the debonding is a precursor of cohesive failure. If one considers the very good agreement between the calculated palatal gap, the FE tensile stress plot, and the fracture locations in the dentin (Fig 6 H post and Figs 8c and 8d), then the present data suggest that adhesive failure of the cement, partial or total, precedes cohesive failure of the other components, ie dentin or ceramic. This correlation further validates the predictive FEA method employed.

The scattering of the results for group B can be explained by the role played by the bonding layer, the individual variability of the fracturing properties of the human dentin, and increased incidence of small imperfections which act as stress concentrations resulting from the manual preparation of the H slot. It is reasonable to assume that a more standardized preparation with a closer internal fit will help to reduce scattering of the data. Furthermore, in the present study single-rooted maxillary premolars were used, which seem to be more susceptible to root fractures when submitted to occlusal loading.[15] Normally, loading forces at 45 degrees are applied; these are associated with more unfavorable stresses during function and are considered the worst-case scenario with regard to the fracture resistance. In the present study, however, the samples carrier was studied at an inclination of 30 degrees.[15] This must be taken into consideration when comparing the results of different studies. It may also explain why Zicari et al[15] previously found lower fracture resistance ranging between 400 N and 550 N when using RelyX Unicem or Panavia P2.0 for the cementation of 5 mm and 7.5 mm glass-fiber posts in specimens. Their specimens also had no ferrule preparation. Another factor that may have led to this discrepancy is that the authors of the latter study submitted their teeth to additional chewing simulation, which was not the case in the present set-up. Differences in the adhesive materials may also contribute to different results. It must be highlighted as a limitation of the present study that lithium disilicate ceramic material was not used in groups C and D as well. In using a ceramic material with a higher fracture toughness such as lithium disilicate, it was possible to isolate the structural effects of the H-design and this is shown by the increase in the number of irreparable fractures in group B. Considering that the aim of the present study was to analyze primarily the effects on the H-shape of the post, the use of lithium disilicate for groups C and D was not warranted. It is reasonable to consider that an increase in the fracture toughness of the ceramic will result in an increase in the number of irreparable fractures for group C. This inference is supported by the relative frequencies of reparable fractures, which are very close when glass-ceramic is used (90% and 100% for groups A and C respectively) and then drop to 70% in group B when lithium disilicate is employed (Table 4).

The present results show that the mode of failure of the restored tooth is ultimately influenced by the fracture strength of the ceramic. For this study, homogenous materials (glass-ceramics and lithium disilicate) were used, and a higher fracture strength of the H post resulted in a stronger restoration.

Novel hybrid ceramics such as resin nanoceramics (eg, LAVA Ultimate)[16] or interpenetrating network ceramics (eg, VITA Enamic)[17,18] show good flexural strength with elastic modulus values in the range of the natural tooth substance. Such hybrids are emerging as alternative materials for milled restorations, offering a combination of high fracture strength and low elastic modulus. Whilst their flexural strength is situated in the same range as that of the homogenous ceramics used in the present study, the failure mechanism is significantly different because of the crack-stopping features embedded within the material. As such, the results of the present study are not directly transposable to these materials; although we can safely suggest that the local environment is favorable for the crack to initiate, it cannot be assumed that this will lead to catastrophic failure as is the case with homogenous ceramics. Additionally, the damping provided by their low elastic modulus coupled with their inherent crack resistance may provide better resistance to separation. Therefore, such materials could be an interesting subject for further research.

An important point to make is the innovative profile of the present study, in which we have taken a concept, tested it numerically, used the numerical data to select the material, and tested it in vitro, showing the validity of the process and how engineering methods can be successfully applied in dentistry.

It must be mentioned, however, that no thermomechanical loading was applied in the present feasibility study. The impact of thermocycling and mechanical stress on the retention strength and the fracture behavior play an important role in long-term predictability. Therefore, the results must still be considered with caution, and more research is justified on this clinically relevant topic.

In terms of clinical application, this design can constitute a valid clinical solution, particularly in those cases where a ferrule cannot be placed, crown lengthening is impractical, or obstructions of the root canal prevent an adequate apical extension of a conventional post. Because of its lightweight design it is also conservative and allows for preservation of the tooth structure, whereas to achieve a similar stiffness, a cylindrical post would require a uniform radius, which may be clinically impossible to achieve without massive dentin removal. Furthermore, the restoration can be completed in one appointment providing that a CAD/CAM system is readily available.

The shape of the preparation is simple, and can be completed using a normal high-speed handpiece with an appropriate diameter cylindrical bur. The minimal dentin depth of the preparation (only about 2 mm) allows for direct vision control so that parallelism can be easily achieved.

For the preparation, the web (ie, the horizontal component of "H") should be aligned with the buccolingual bending axis of the tooth. The flanges (ie, the vertical components of the "H") should be positioned as far buccally and lingually as possible. This is based on the analytical solutions of the bending of beams, in which the location of the flanges should be too far away from the neutral axis (ie, mesiodistal axis of the tooth) to increase the resistance to bending. In positioning the flanges buccally and lingually away from the neutral axis, a minimum of 0.5 mm sound dentin should be left between the flanges and the margin of the preparation. We would recommend for 1 mm or more of sound dentin to circumscribe the preparation and for at least 1 mm of dentin to be "caught" between the flanges to allow for sufficient resistance. The thickness of the H should be at least 0.5 mm to allow for milling and/or casting. For finishing, the outline of the preparation should be rounded to prevent stress concentrations.

CONCLUSION

The present study tested the hypothesis that a short post with a modified design can deliver improved mechanical behavior in severely compromised endodontically treated teeth. It was shown that a short H-shape post in a non-ferruled preparation increases the fracture strength of the restoration. As mentioned, further work is needed to properly explore the biomechanical behavior of the modified post, but within the limitations of the study it can be concluded that an H-shape post may constitute a viable alternative to restoring severely compromised teeth.

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