Effects of Central Retainer Depth on Stress Distribution and Fracture Resistance in Endocrown-restored Maxillary Premolars: 3D Finite Element and in vitro Analysis

You Sheng JIANG[1], Lin FENG[2], Jun Xin ZHU[3], Xiao Yan WANG[2], Xue Jun GAO[2]

Objective: *To explore how central retainer depth affects stress distribution and fracture resistance in endocrown-restored premolars.*

Methods: *A 3D finite element (FE) model of an intact maxillary premolar was established as a negative control. Five endocrown-restored FE models were established, differing in the extension of the central retainer inside the pulp chamber: 0, 2, 3, 4 and 5 mm. The remaining pulp cavity was filled with composite resin. Stress distributions were analysed under oblique loads. Thirty freshly extracted human maxillary premolars were randomly divided into three groups after endodontic treatment. The extension of the central retainer was set to 0 (G0), 2 (G2) or 4 mm (G4). After endocrown manufacturing and cementation, all specimens were subjected to oblique loads in a universal testing machine until fracture occurred. Fracture resistance was analysed by one-way analysis of variance (ANOVA). Fracture patterns were analysed using a Fisher exact test ($\alpha = 0.05$).*

Results: *The FE analysis showed that within a range of 0 to 4 mm, increasing retainer depth led to decreased peak von Mises Stress (VMS) values in the cement layer and tooth cervix. At a retainer depth of 5 mm (without base material), peak VMS values were higher than those parameters at a depth of 4 mm. The mean fracture resistance values increased with the increasing retainer depth. G4 exhibited significantly higher fracture resistance than G0. The proportion of irreparable fractures increased with retainer depth.*

Conclusion: *A central retainer with composite resin used as base material and extending approximately 1 mm apical to the cementoenamel junction is recommended for endocrown-restored premolars.*

Keywords: *3D finite element analysis, endocrown, fracture resistance, maxillary premolar, tooth defect*

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Conventional methods in the restoration of endodontically treated premolars include full crowns and post-core crowns.[1] Both techniques require removal of dental tissue in the tooth cervix to acquire extra-coronal retention, which may further weaken the resistance of the original dental tissue.

With the increasing emphasis placed on minimally invasive procedures and tooth resistance preservation, endocrown restoration, first reported by Bindl and Mörmann[2] in 1999, offers a novel therapeutic option. An endocrown refers to a restoration comprising a crown and a central retainer that extends into the pulp chamber. An endocrown, with the original loss of tooth structure used to achieve retention, can preserve dental tissue in the tooth cervix area and may reliably resist normal occlusal forces.[3] Clinical studies on endocrown restorations have reported encouraging medium- to long-term outcomes, with survival rates ranging from 81.8% to 100% over follow-up periods of 2 to 7 years.[4-8]

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A systematic review suggested that endocrowns demonstrated comparable biomechanical performance to traditional post, core and crown restorations in endodontically treated teeth.[9]

Despite increased adoption of endocrowns for molar restoration, there is concern that the central retainer's extension inside the pulp chamber generates concentrated stress within the tooth. Premolars restored with endocrowns are more susceptible than molars due to their smaller bonding area, thinner dental wall and greater lateral force endured.

Rational design of the central retainer is crucial to avoid stress concentration. Bozkurt et al[10] highlighted that the extension depth in an endocrown played a crucial role in mechanical stability. Although several studies have investigated the influence of central retainer depth on biomechanical performance of lithium disilicate glass ceramic endocrowns, these findings remain inconsistent. Some reported no significant effect of pulpal extension on fracture resistance,[11] whereas others observed improved resistance with deeper extensions[12,13] or a decrease-increase trend with intermediate depth yielding the lowest performance.[14] Moreover, no study has anchored central retainer depth to an anatomical landmark such as the cementoenamel junction (CEJ), leaving clinicians without evidence-based guidance for premolar-specific endocrown design.

The purpose of this study was to investigate the effects of central retainer depth on stress distribution and fracture resistance in maxillary premolars, thus providing guidance for clinical applications involving endocrown-restored premolars. The methods in this study included 3D finite element (FE) analysis and an in vitro fracture resistance test. The null hypothesis was that, under certain conditions, the central retainer depth inside the pulp chamber would not negatively influence stress distribution and fracture resistance in endocrown-restored premolars.

Materials and methods

3D FE analysis

An intact maxillary second premolar extracted for orthodontic reasons was used for microcomputed tomography (microCT) scanning (eXplore Locus SP, GE Healthcare, Chicago, IL, USA). The enamel, dentine and pulp were divided into three portions using an interactive medical image control system (Mimics 15.0, Materialise, Leuven, Belgium), and the contour of each portion was reconstructed and materialised using Geomagic Studio (Geomagic, Research Triangle Park, NC, USA). A 3D solid model was obtained through CATIA (V5R20, Dassault Systèmes, Velizy-Villacoublay, France). A cuboid simulating the alveolar bone was generated 1 mm below the lowest point of the CEJ, including cortical bone with a thickness of 2 mm. The alveolar bone was connected to the model by a 0.2-mm-thick periodontal ligament. The reconstructed model (model S) was imported into the FE software (Abaqus 2017, Dassault Systèmes) to serve as a negative control.

To simulate a defective tooth before restoration, model D was constructed in Creo 4.0 (PTC, Boston, MA, USA) and Hypermesh 14.0 (Altair Engineering, Troy, MI, USA) based on model S. The 5-mm-depth pulp space was divided into root canal space and a pulp cavity by a horizontal plane placed 2 mm below the lowest point of the CEJ. The tooth was sectioned parallel to the occlusal surface 3 mm above the CEJ, stimulating the shoulder of the remaining tooth. The total depth of the pulp cavity was fixed at 5 mm.

FE models with central retainers of various depths were then established (Fig 1a and b). The depth of the central retainer of the endocrown restoration was defined as the vertical distance from the shoulder surface of the remaining tooth to the end of the endocrown retainer. Central retainer depths in different models were set to 0 (model V), 2 (model E2), 3 (model E3), 4 (model E4) and 5 mm (model E5). Because the total depth of the cavity was 5 mm, in models V, E2, E3 and E4, the remaining pulp cavity was filled with composite resin (Filtek P60, 3M, St. Paul, MN, USA) as the base material.

A lithium disilicate–reinforced glass-ceramic (IPS e.max CAD blocks, Ivoclar Vivadent, Schaan, Liechtenstein) was chosen as the restoration material. A 0.12-mm-thick cement layer was constructed on the internal surface of the restoration using a cohesive element. All models were meshed using Hypermesh 14.0 software. Mechanical properties of the materials, including elastic modulus and Poisson ratio, were attributed to each structure of the finite element model (Table 1).[15-21] All materials were assumed to be homogeneous, isotropic and linearly elastic. An oblique load of 200 N, at 30 degrees to the long axis of the tooth, was applied to the prepared occlusal surface of model D and the inclined surface of the palatal cusp of other models (Fig 2). The mesial, distal and bottom surfaces of the alveolar bone cuboid were fixed in all directions. The distribution and magnitude of the von Mises Stress (VMS) in the tooth tissue and cement layer were calculated. The magnitude of the peak VMS values and the differences in stress distribution were compared.

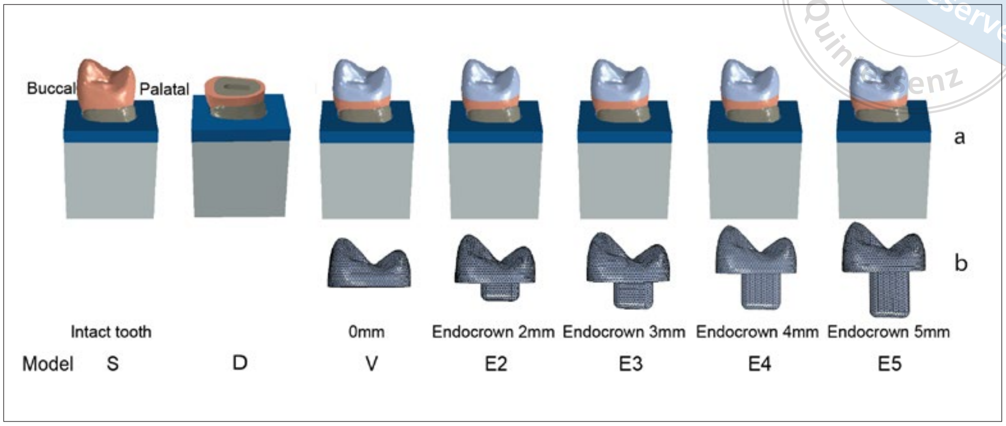

Fig 1a and b FE models of models S, D, V, E2, E3, E4 and E5 **(a)**. Various central retainer depths for models V, E2, E3, E4 and E5 **(b)**.

Table 1 Material properties.

Material	Elastic modulus (MPa)	Poisson ratio
Enamel[15]	84,100	0.33
Dentine[15]	18,600	0.31
Periodontal ligament[16]	70	0.45
Cortical bone[17]	13,700	0.30
Cancellous bone[17]	1,370	0.30
IPS e.max CAD[18,19]	10,000	0.20
Resin cement[20]	5,000	0.29
3M Filtek P60[21]	19,700	0.32

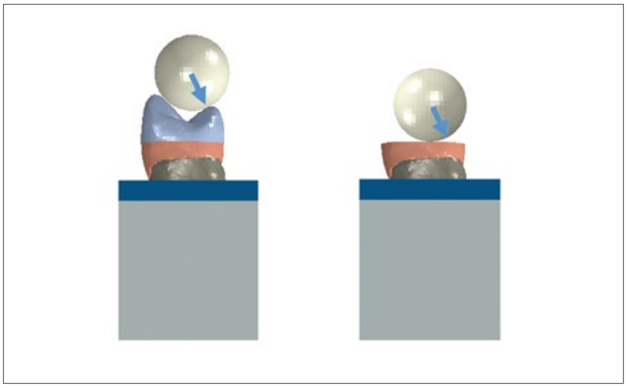

Fig 2 Oblique load of 200 N at 30 degrees to the long axis.

Fracture resistance testing

Thirty sound human single-rooted maxillary second premolars freshly extracted for orthodontic reasons were selected. One-way analysis of variance (ANOVA) showed no significant differences (P > 0.05) in root length, mesiodistal width or buccolingual width. This study was approved by the Ethics Committee of Peking University School of Stomatology (PKUSSIRB-202056093). The extracted human teeth were collected with patient consent and in accordance with institutional guidelines.

The teeth were sectioned parallel to the occlusal surface to a level 3 mm above the lowest point of the CEJ using a sectioning machine (SYJ-150, Shenyang Kejing Auto-Instrument, Shenyang, China). Root canals were prepared using a rotary nickel-titanium system (ProTaper Universal, Dentsply Maillefer, Ballaigues, Switzerland), rinsed with 1.25% sodium hypochlorite and filed with a master apical file #30. They were then filled to 2 mm below the CEJ with gutta percha (Dentsply Maillefer) and sealer (AH-Plus, Dentsply Maillefer) using a hot continuous-wave condensation technique. The root access was filled with composite resin (Filtek P60, 3M) to the level of the section. All teeth were stored in distilled water at 37°C for 24 hours.

The teeth were randomly divided into three groups (G0, G2 and G4, n = 10 each) and prepared with different depths of extension in the pulp chamber (Fig 3). The extension of the central retainer was set to 0 (G0, no cavity prepared), 2 (G2) or 4 mm (G4). Cavity preparations were limited to the removal of undercut areas and maintenance of the anatomic configuration of the pulp chamber. The axial walls had an internal taper of 8° to 10°. Internally, the extension on the shoulder level was approximately 2 mm in the mesiodistal direction and 4.5 mm in the buccolingual direction.

A plastic dental typodont was used to position the teeth. After preparation, each tooth was located at the maxillary second premolar site. Digital optical impressions were taken using a chairside intraoral scanner (Cerec3, Sirona Dental Systems, Bensheim, Germany). After construction of the virtual models, the endocrowns of each group were milled with IPS e.max CAD blocks and crystallised in accordance with the manufacturer's instructions. Before bonding, precision fit and marginal adaptation of endocrowns were evalu-

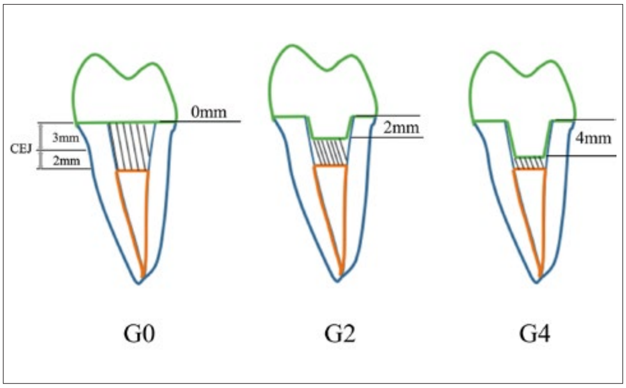

Fig 3 Endocrown-restored premolars with various central retainer depths. G0, 0 mm; G2, 2 mm; G4, 4 mm.

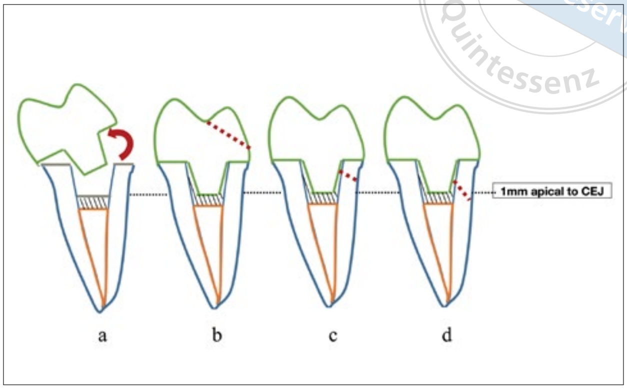

Fig 4a to d Fracture pattern. The red dashed line indicates the fracture line. The black dotted line indicates the position 1 mm apical to the CEJ. Debonding at the restoration-tooth interface **(a)**; cohesive failure of the endocrown **(b)**; repairable fracture: fracture line located ≤ 1 mm apical to the CEJ **(c)**; irreparable fracture: fracture line located > 1 mm apical to the CEJ **(d)**.

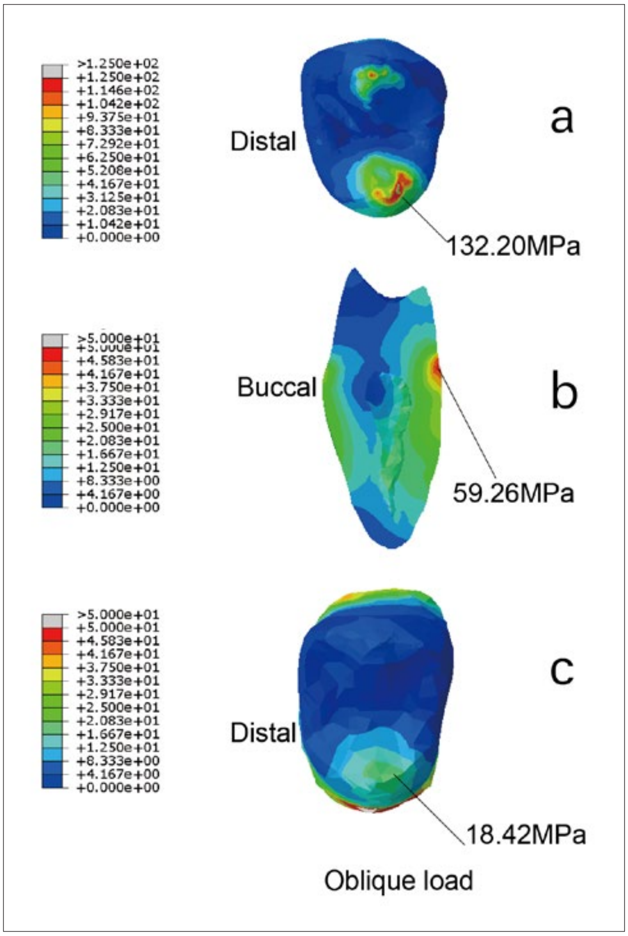

Fig 5a to c VMS distributions (MPa) of the intact tooth. Enamel **(a)**; dentine, sagittal plane **(b)**; dentine, occlusal surface **(c)**.

ated. Cementation surfaces of endocrowns were etched with 5% hydrofluoric acid for 20 seconds (IPS Ceramic Etching Gel, Ivoclar Vivadent), rinsed with water for 30 seconds and dried. A Multilink N restoration bonding kit (Ivoclar Vivadent) was manipulated according to the manufacturer's instructions. The sample was then light cured for 40 seconds on each side and excess cement was removed and polished. Samples were placed in a 37°C distilled water bath for 24 hours.

In fracture resistance testing, a universal testing machine (3367Q7088, Instron, Norwood, MA, USA) was used to apply progressive compressive loading (30 degrees on the palatal cusp) to the teeth until fracture occurred. The crosshead speed was 1 mm·min^{-1}. Fracture strength and fracture modes were evaluated. Specimens with tooth fractures ≤ 1 mm apical to the CEJ or fractures of the restoration were classified as repairable fracture pattern, including specimens with fractures resulting in debonding and cohesive failure of the restoration. Specimens with tooth fractures > 1 mm apical to the CEJ were classified as irreparable fracture pattern (Fig 4a to d). Fracture resistance was analysed by one-way ANOVA. Data normality (Shapiro–Wilk test, $\alpha = 0.10$) and homogeneity of variances (Levene test, $\alpha = 0.05$) were confirmed, justifying the use of parametric one-way ANOVA. Fracture patterns were analysed using a Fisher exact test ($\alpha = 0.05$).

Results

3D FE analysis

The VMS in model S (intact tooth) was concentrated in the tooth cervix, on the palatal surface, with the exception of the loading area (Fig 5a to c).

Figure 6 illustrates the stress distributions of model D and model E4, with the latter serving as a representative of endocrown-restored models. In model D,

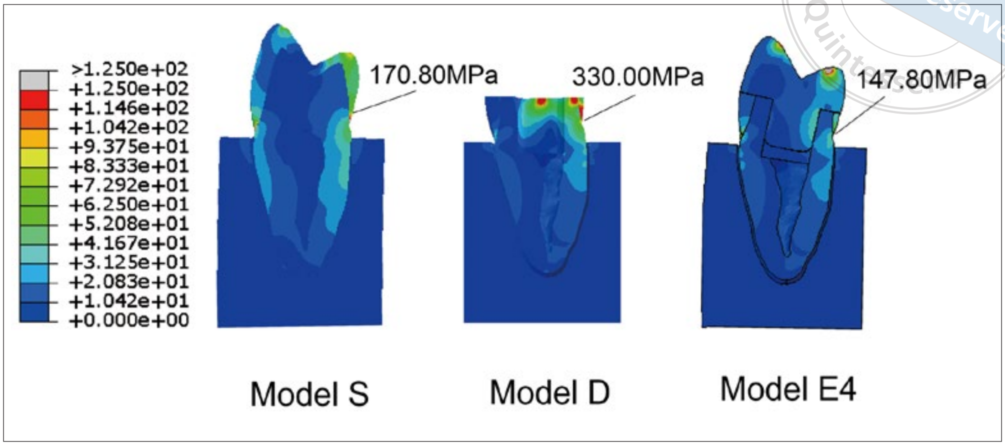

Fig 6 VMS distributions (MPa) of the intact tooth (model S), defective tooth (model D) and endocrown-restored tooth (model E4, 4 mm retainer depth) under an oblique load.

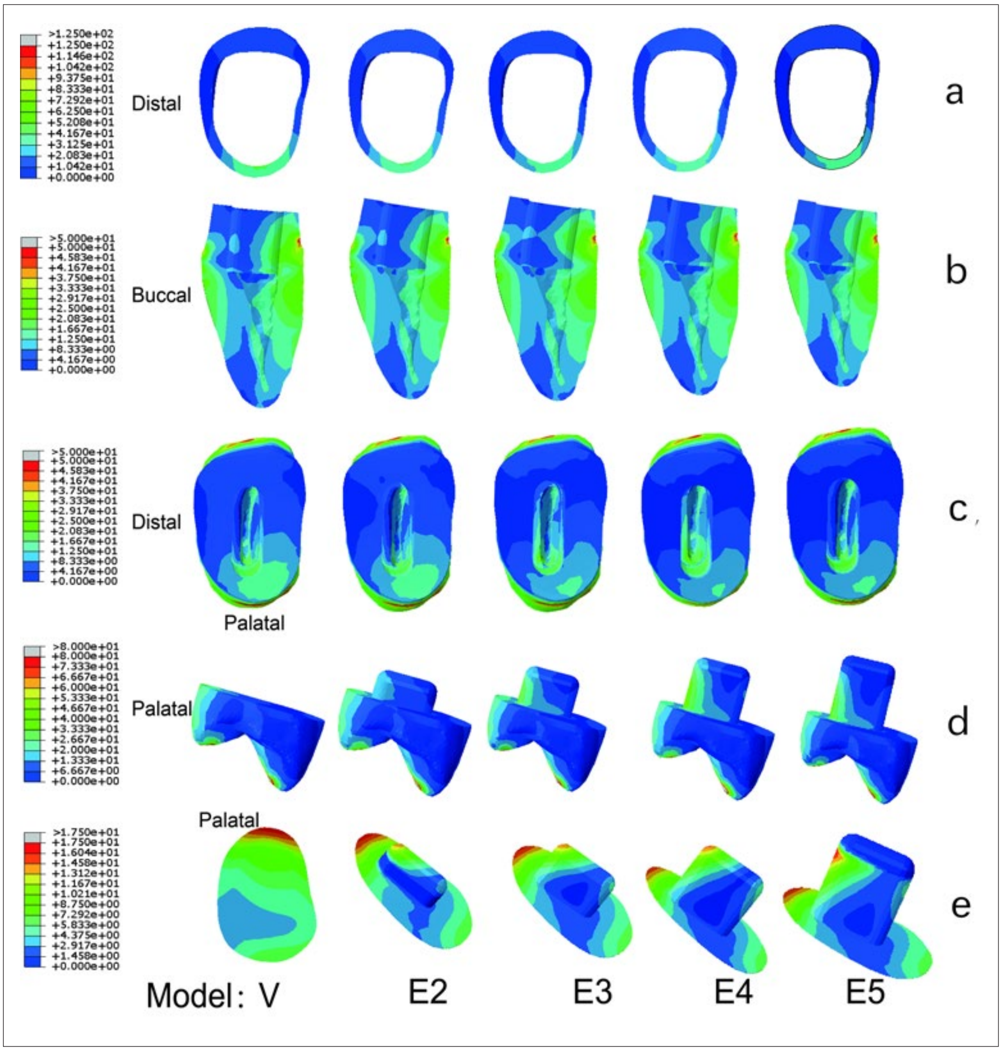

Fig 7a to e VMS distributions (MPa) in teeth restored using endocrowns with various retainer depths and subjected to an oblique load of 200 N. Enamel **(a)**; dentine **(b and c)**; restoration **(d)**; cement layer **(e)**.

without restoration of the defective tooth, compared with model S, the VMS was concentrated in the section plane, extending into the pulp cavity, and the values were greater. In model E4, after restoration with an endocrown with a retainer depth of 4 mm, compared with model S, the regions of concentrated VMS were similar: mainly on the palatal cervix and partially on the shoulder surface.

Table 2 Peak VMS values (MPa) of enamel, dentine, cement layer, base material and restoration under oblique loads.

Model	Enamel	Dentine	Cement layer	Inner palatal wall
V	160.70	61.80	17.73	21.07
E2	158.50	60.96	17.38	21.18
E3	152.70	58.79	16.77	22.01
E4	147.80	57.04	16.01	21.66
E5	152.00	58.84	17.97	23.79

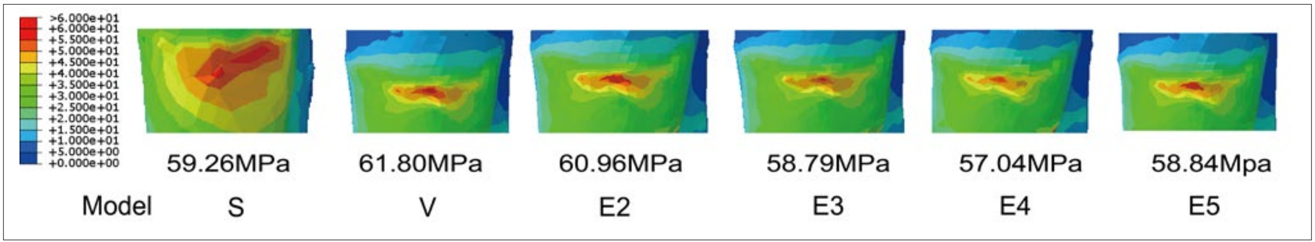

Fig 8 VMS distributions of dentine in the palatal cervix (MPa) under an oblique load of 200 N.

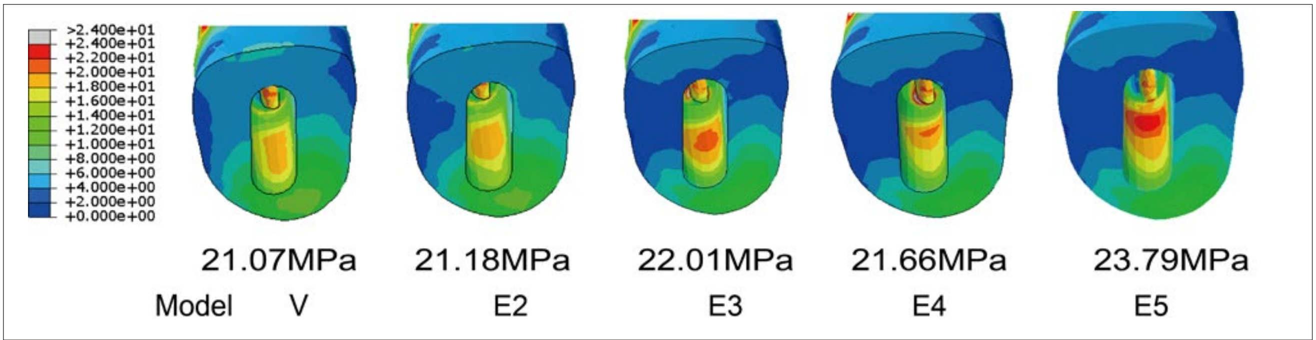

Fig 9 VMS distributions (MPa) on the palatal wall of the pulp chamber under an oblique load of 200 N.

Peak VMS values in endocrown-restored teeth with various central retainer depths were consistently observed on the palatal cervix of the tooth (Fig 7a to e).

In the occlusal view (Fig 7c), VMS in dentine at the shoulder surface progressively decreased with increasing retainer depth from 0 (model V) to 4 mm (model E4), but increased markedly d in model E5 (5 mm depth without a resin base). From the outer surfaces of the tooth cervix, when composite resin was used as the base material (models V, E2, E3 and E4), increasing retainer depth led to decreased peak VMS values of dentine and enamel in the palatal cervix and dissipation of the VMS. Model E5, without base material, had larger peak VMS values and a higher stress concentration compared with model E4. Model E4 had the lowest peak VMS value among the endocrown-restored models (Table 2 and Fig 8).

Inside the pulp chamber, peak VMS values consistently occurred on the inner palatal wall of the pulp chamber, but much smaller than those measured in the palatal cervix on the outer surface of the tooth (Table 2 and Fig 9). The migration pattern of the location of the peak VMS values was also examined in detail: under oblique loads, when the end of the retainer was located beyond the CEJ, as in models V, E2 and E3, peak VMS values occurred at approximately the same level as the CEJ. However, when retainer depth exceeded the CEJ, as in models E4 and E5, the location of peak VMS values moved apically and beyond the CEJ (Fig 10). Among all endocrown-restored models, peak VMS values were highest in model E5, without base material.

In model E3, with composite resin as base material and extension of the retainer to the CEJ level, peak VMS values were larger than those of models V, E2 and E4.

Fracture resistance testing

The mean fracture resistance values increased with increasing retainer depth (Fig 11). One-way ANOVA revealed a statistically significant difference between G0 and G4 ($P < 0.05$).

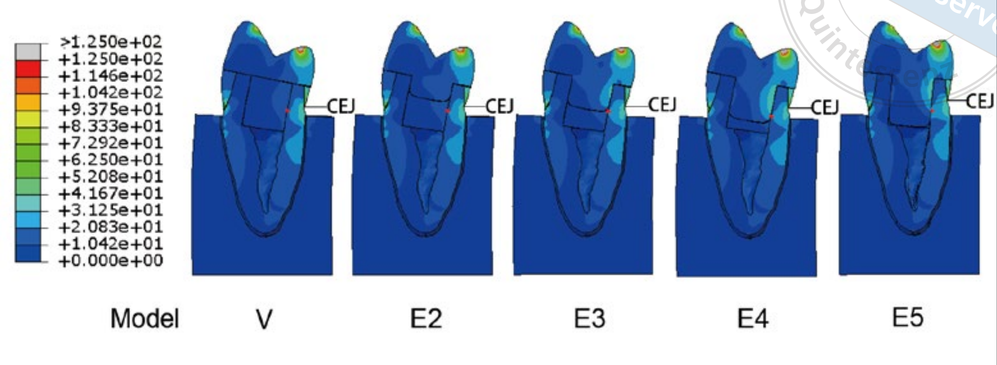

Fig 10 VMS distributions (MPa) in endocrown-restored teeth under an oblique load of 200 N. Red dots show the location of the peak VMS values inside the pulp chamber.

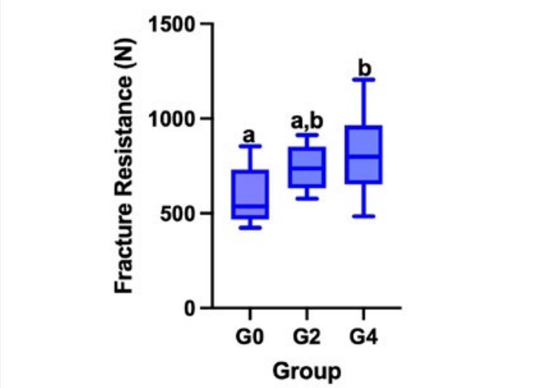

Fig 11 Boxplots of the load-to-failure results. The box represents the spreading of the data between the first and third quartiles. The central horizontal line represents the mean. The whiskers extend to the minimum and maximum values measured. Different letters for the groups denote significant differences ($P < 0.05$).

Under oblique loading, fractures mainly occurred on the palatal side of the restoration or on remaining tooth tissue. Analysis of the fracture pattern showed that the cracks tended to move apically with increasing retainer depth and that the proportion of irreparable fractures increased in the order G0 < G2 < G4, comprising 20%, 50% and 80%, respectively (Fig 12). Pairwise comparisons revealed that the proportion of irreparable fractures was significantly higher in group G4 than in group G0 ($P < 0.05$). Group G4 had the highest load-to-failure values, along with a predominance of irreparable fractures.

Discussion

Can the overall resistance of the tooth be restored by endocrown restoration?

Endocrown restoration has raised clinical concerns due to the extension of the central retainer deep into the pulp chamber, potentially generating greater stress on the internal dental walls. According to the present study, peak VMS values were much lower inside the pulp chamber than on the outer surface of the tooth cervix.

Unlike the stress concentration inside the pulp chamber of the unrestored tooth, the stress distribution patterns and tendencies of endocrown-restored teeth were similar to those of an intact premolar. Peak VMS values occurred in the tooth cervix, demonstrating the potential advantages of an endocrown in restoring the overall resistance of the tooth. Endocrown restoration may alleviate stress concentration inside the pulp chamber through two mechanisms: endocrown preparation preserves the resistance of the tooth cervix, where the stress is concentrated after restoration, and appropriate design of the central retainer allows stress transmission and dispersion within the dental tissue. As illustrated in the occlusal view of Fig 7c, the shoulder surface exhibits a stress trend consistent with that observed at the cervical region: VMS is minimised at a retainer depth of 4 mm but markedly increases when the preparation extends to 5 mm without a resin base. The shoulder surface of the tooth bears part of the stress transmitted by the endocrown restoration and may partially counteract stress concentration inside the pulp chamber.

Thus, in terms of stress distribution, preservation of dental tissue in the cervix and appropriate design of the central retainer can mitigate the stress generated

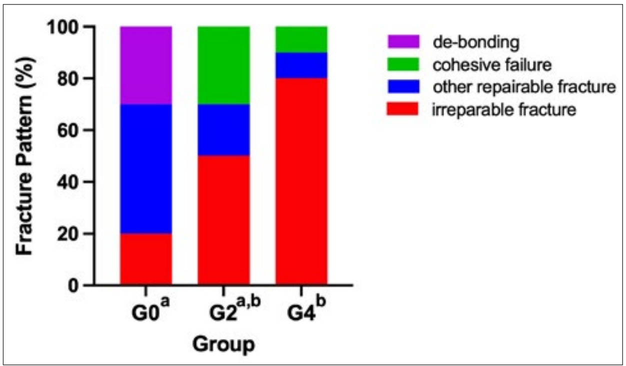

Fig 12 Frequencies of failure pattern in percentages. Different letters of the groups denote significant differences in irreparable fracture ($P < 0.05$).

by the endocrown inside the pulp chamber, such that it does not contribute to an irreparable fracture. The present authors' null hypothesis, that under certain conditions, the depth of the central retainer inside the pulp chamber would not cause catastrophic negative effects on the stress distribution and fracture resistance of endocrown-restored premolars, was therefore validated.

Is there an optimal endocrown retainer depth?

In the present study, the 4-mm retainer group demonstrated the highest fracture resistance, consistent with FE analysis predictions of reduced peak VMS on the outer cervical surface at this depth. Although increasing retainer depth elevated VMS values on the inner pulp chamber wall, the overall peak VMS values remained consistently lower within the pulp chamber than on the external cervical dentine across all endocrown models. Moreover, the location of intrapulpal peak VMS shifted apically with greater depth, indicating progressive downward transmission of occlusal loads, a biomechanical behaviour that may contribute to enhanced load distribution when properly managed. These findings align with prior in vitro investigations: de Kuiper et al[11] and Dartora et al[12] reported superior load-to-failure values for deeper endocrown extensions in posterior teeth, corroborating the general trend that increased central retainer depth enhances mechanical performance. Additionally, Zhong et al[22] demonstrated that a 4-mm lithium disilicate endocrown in the maxillary first molar exhibited the lowest maximal Mohr-Coulomb stress ratio under lateral loading compared to 3- and 5-mm designs, suggesting a more favourable stress distribution.

However, the FE analysis also revealed a critical anatomical consideration: the central retainer should avoid alignment with the CEJ. As shown in Table 2, model E3, whose end of the retainer coincided with the palatal CEJ, exhibited higher intrapulpal peak VMS than both shallower and deeper configurations. Notably, this observation is supported by Dartora et al,[12] who, using FE analysis in molars, found that a 3-mm endocrown extension (approximately at the CEJ level) generated higher cervical VMS than either 1- or 5-mm designs. Similarly, Hayes et al[14] observed a dip in fracture resistance at 3 mm in molars, with both 2- and 4-mm groups performing better. Collectively, these data identify the CEJ as a biomechanical risk position, where abrupt changes in dental wall thickness and chamber geometry amplify stress regardless of absolute depth.

Despite the mechanical advantages of deeper extension, clinical consequences cannot be ignored. The 4-mm group, despite exhibiting the highest fracture resistance, suffered a significant clinical cost: 80% of fractures in this group were irreparable, compared to only 20% in the 0-mm group. This outcome was also supported by the FE findings: greater retainer depth shifted the intrapulpal peak stress apically (Fig 10), promoting crack initiation deeper within the root and thereby increasing the likelihood of irreparable fractures. This trade-off between fracture resistance and fracture pattern is echoed in the literature. Pedrollo Lise et al[13] found that 2.5-mm lithium disilicate endocrowns in premolars produced significantly more repairable failures than 5-mm designs under oblique loading. Likewise, Hayes et al[14] reported that 2-mm extensions in molars resulted in more favourable (repairable) fracture patterns than 3- or 4-mm groups. Although enhanced load bearing capacity may delay initial fracture under occlusal forces, fractures in deeper designs are more likely to be irreparable, limiting options for rehabilitation. In contrast, repairable fractures often allow re-restoration or minor intervention. Thus, maximising fracture resistance alone is insufficient if the failure pattern compromises long-term tooth prognosis.

Within the parameters of this study, a central retainer depth of 4 mm, combined with a composite resin base and extending approximately 1 mm apical to the CEJ, represents the optimal compromise for maxillary premolars, offering high fracture resistance (supported by both FE analysis and in vitro testing) and an acceptable fracture risk, attributable to its favourable stress distribution observed in FE analysis. Nevertheless, clinicians should remain cognisant that even this optimised design, despite being less prone to fracture, may result in irreparable failures once fracture occurs, underscoring the importance of appropriate case selection. Treatment planning must therefore be individualised, taking into account patient-specific risk factors such as excessive occlusal or parafunctional loading, as well as the residual structural integrity of the tooth cervix and coronal third of the root (e.g., thin dentinal walls, wedge-shaped defects, root caries or resorptive lesions).

Does a composite resin base material play a role in stress distribution?

Adhesive resin materials are commonly used under the endocrown to seal the root canal and fill undercuts. The FE analysis showed that a 5-mm retainer without a base material resulted in higher cervical VMS values than a 4-mm retainer with a base material. This finding suggested that, although increasing depth is conducive to stress conduction to the root, in the absence of composite resin underneath the endocrown, which can provide a supporting foundation and buffer the stress, this advantage is no longer realised. The composite resin base appears to function as both a structural support and a viscoelastic buffer, mitigating stress concentration at the ceramic–dentine interface by promoting more uniform load transfer across the restoration–tooth complex. This mechanism aligns with recent evidence from Zheng et al,[23] who demonstrated that composite resin reinforcement of thin residual lateral walls in endodontically treated premolars significantly improved fracture resistance and altered crack propagation patterns.

Clinical implications

An endocrown is a feasible option for restoring endodontically treated premolars, offering the advantage of preserving dental tissue in the tooth cervix and potentially enhancing fracture resistance. Investigating the effects of central retainer depth on stress distribution and fracture resistance is essential to provide clinical guidance for the optimal design of endocrowns.

Limitations

The present study has several limitations. First, the FE models assumed all materials to be homogeneous, isotropic and linearly elastic, a simplification that does not fully reflect the anisotropic, viscoelastic and heterogeneous nature of real tooth and periodontal structures. Second, optimal bonding was assumed at all interfaces, whereas clinical scenarios often involve microgaps, time-dependent degradation or imperfect adhesion. Third, the fracture resistance testing applied a single static load without cyclic fatigue testing, which limits the simulation of the intraoral environment and long-term clinical performance under thermal and mechanical aging. Finally, future in vitro studies including intact teeth or unrestored defective teeth as additional control groups are likely to provide more comprehensive insights into the biomechanical implications.

Conclusion

A central retainer depth of approximately 1 mm apical to the CEJ with a composite resin base appears to offer the best compromise between fracture resistance and risk of fracture. Although fractures are uncommon with this design, they may involve a higher proportion of irreparable failures compared to shallower designs, highlighting the importance of appropriate case selection. FE analysis suggests that the use of composite resin as a base material facilitates stress distribution in the tooth cervix and cement layer.

Conflicts of interest

The authors declare no conflicts of interest related to this study.

Author contribution

Dr You Sheng JIANG contributed to the methodology, investigation and writing of the original draft; Dr Lin FENG contributed to the conceptualisation, writing, reviewing and editing; Drs Jun Xin ZHU and Xiao Yan WANG contributed to the software and resources; Dr Xue Jun GAO contributed to the supervision and project administration.

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