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Effect of remaining pericervical dentin on biomechanical behavior of endocrown-restored molars with different materials: Three-dimensional finite element and Weibull analyses

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To evaluate the effect of remaining pericervical dentin (PCD) on the biomechanical behavior of endocrown-restored molars with different materials, six three-dimensional finite element (FE) models were reconstructed with different thicknesses and heights of pulp-chamber lateral dentinal wall (PCLDW). IPS Empress 2, In-Ceram Zirconia, and Lava Ultimate were selected as the materials. Compared with the Lava Ultimate FE models, the maximum tensile stress in the FE models using ceramics was higher in the endocrown and lower in the PCD surrounding it, and the overall failure probabilities with different PCLDW thicknesses and heights were similar, ranging from 9.8% to 12.9% under the normal lateral masticatory force, which were lower than the FE models using Lava Ultimate (ranging from 13.4% to 15.1%). Considering the bonding properties of ceramics, endocrown-restored molars using etchable lithium disilicate-reinforced glass ceramic exhibit superior longevity due to the stress shielding effect, regardless of the thickness and height of PCLDW.

Keywords: Endocrown, Finite element analysis, Restorative materials, Stress shielding effect

INTRODUCTION

Complete crowns are commonly used to restore endodontically treated posterior teeth with coronal loss due to their favorable clinical performance and satisfactory survival rate[1,2]. Plenty of healthy dental hard tissues have to be removed during preparation for complete crowns[3], thus decreasing the resistance of residual tooth structure. For endodontically treated posterior teeth who cannot supply enough retention for complete crowns, post-and-core systems combined with crowns are recommended[4,5]. However, it is also not an ideal technique because of the disadvantages of damaged coronal obturation and weakened root canal walls during preparation, which increase the risks of root canal recontamination and tooth fracture. Furthermore, in situations where the quantity of dental hard tissues in the tooth cervix is limited, or the root canals are short or calcified, there is insufficient space left to prepare a ferrule or place an intracanal post. As alternative techniques, some emerging technologies, including the use of endocrowns, have been proposed to mitigate these shortcomings. The term “endocrown” was introduced by Bindl and Mörmann in 1999[6], and has been increasingly used in recent years with advances in bonding techniques and restorative materials. Previous *in vitro* studies demonstrated that the fracture resistance of endodontically treated posterior teeth restored with endocrowns was similar to or even better than that of posterior teeth restored with post-and-core systems and crowns[7-9]. Clinical studies revealed that there was no significant difference in the survival rates of teeth restored with endocrowns and traditional restorations[10,11], indicating that an endocrown is an alternative prosthesis for restoring endodontically treated posterior teeth.

In the teeth restored with diverse prosthetic restorations, the cervical region is commonly perceived as a dangerous zone because of stress concentration[12-15]. The presence of ferrule has been proven to be beneficial for the reparative effect of teeth restored with complete crowns or post-and-core systems combined with crowns[16,17]. Recent studies also found that the fracture resistance of endocrown-restored posterior teeth with ferrule was superior to those without ferrule[16,18]. As the standard endocrowns are considered as adhesive monolithic restorations anchored in the pulp chamber without ferrule, the biomechanical behavior of posterior teeth restored with standard endocrowns in the cervical region should be further studied. In 2010, Clark and Khademi proposed the concept of pericervical dentin (PCD), defined as the dentin adjacent to crestal bone extending from the coronal 4 mm to the apical 4 mm of it[19]. PCD is considered to play an important role both biologically and biomechanically. From a biomechanical perspective, it acts as a transition structure and transfers occlusal stress to the root, consequently decreasing the risk of tooth fracture. Therefore, it is reasonable to assume that the quantity of PCD may affect the longevity of restored teeth. In the teeth restored with standard endocrowns, the remaining PCD can be measured by the height and thickness of the pulp-chamber lateral dentinal wall (PCLDW). To date, the influence of PCLDW height on the reparative effect of endocrown-

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restored molars remains controversial. Some authors considered that it could affect the biomechanical performance of restored molars[20], while some other authors considered that no significant difference was found in the endocrown-restored molars with different lateral dentinal wall heights[18,21]. In addition, to the authors' knowledge, little information is known about the relationship between the PCLDW thickness and reparative effect of endocrown-restored teeth. To assess the prognosis of endodontically treated posterior teeth preoperatively, and to improve the survival rate of restored teeth, it is necessary to determine the effect of PCLDW height and thickness on the biomechanical behavior of teeth restored with endocrowns.

Debonding of endocrowns is the primary cause of restoration failure, followed by periodontitis and endocrown fracture[22]. Stress concentration is an important reason for both debonding and fracture, so the patterns of stress distribution in the endocrown-restored teeth should be investigated. Finite element (FE) analysis is regarded as a reliable research tool and has been widely used in the medical domain. Therefore, we examined the stress distributions in endocrown-restored molars with different thicknesses and heights of PCLDW using FE analysis. Restorative material type could influence the stress distributions in restored teeth. Similar to the material choice of complete crowns, some clinicians select lithium disilicate-reinforced glass ceramic as the restorative material for endocrowns due to its good aesthetic performance and similar elastic modulus to that of enamel; some other clinicians prefer using zirconia-based ceramic as the restorative material due to its well mechanical properties. Despite the increased use of high-temperature polymerized composite resin recently, its effect on the biomechanical performance of endocrown-restored posterior teeth remains controversial[23,24]. Therefore, three frequently used restorative materials clinically were selected in present study, and the Weibull function was incorporated with FE analysis to predict the long-term longevity of endocrown-restored molars with different materials. We proposed a null hypothesis that regardless of the material type, endocrown-restored molars with different thicknesses or heights of PCLDW would have similar stress distribution patterns and failure risks. The stress distributions and failure probabilities of endocrown-restored molars were evaluated using FE and Weibull analyses.

MATERIALS AND METHODS

To evaluate the stress distributions and failure probabilities of endocrown-restored molars with different PCLDW thicknesses and heights, six three-dimensional FE models were reconstructed, and were divided into two groups based on the height of PCLDW. Group A included models A-T0.5, A-T1.0, and A-T1.5, representing FE models with different PCLDW thicknesses (0.5, 1.0 and 1.5 mm) and a 1.5-mm PCLDW height. In Group B, models B-T0.5, B-T1.0, and B-T1.5 had the same wall thicknesses as the corresponding Group A models, but the height of PCLDW was increased to 3.5 mm. IPS Empress 2, In-Ceram Zirconia, and Lava Ultimate were selected as the restorative materials.

FE model generation

Based on the modeling approach described in previous study[25], a freshly extracted sound mandibular first molar was scanned using microcomputed tomography (eXplore Locus SP, GE Healthcare, London, Canada). The obtained data was imported into an interactive medical image control system (Mimics ver.15.0, Materialise, Leuven, Belgium), and was then divided into enamel, dentin and pulp portions based on the differences of pixel densities. The three portions were materialized using reversing engineering software (Geomagic Studio ver.11.0, Raindrop Geomagic, Research Triangle Park, NC, USA) to fabricate a solid FE model of mandibular molar. The tooth root below the cementoenamel junction was surrounded by a 0.2-mm layer for periodontal ligament simulation, which was connected to a 13×17×20 mm cuboid for alveolar bone simulation[25].

The thickness of the lateral dentinal wall is not uniform in the direction parallel to the long axis of the molar. To standardize this variable, the thickness of the PCLDW (T) in this study was defined as the width of the PCD in the horizontal plane passing the highest point of the pulp chamber floor; accordingly, the PCLDW height (H) was defined as the vertical distance between the coronal plane of the dental remnant and the horizontal plane mentioned above (Fig. 1a). As the narrowest width of dentin in the horizontal plane passing the highest point of the pulp chamber floor was approximately 1.8 mm, the thickness of the PCLDW was set at 0.5, 1.0 and 1.5 mm (Fig. 1b). According to the concept of PCD, the PCLDW height was set at 1.5 mm and 3.5 mm in the present study (Fig. 1c). From the viewpoint of mechanics, the extension angle of pulp chamber during preparation didn't affect the stress distributions of endocrown-restored molars[25]. So the pulp chamber extension angle in present study was set at 0 degree. Model A-T0.5 was reconstructed as follows. Based on the aforementioned FE model, a horizontal plane passing the highest point of the cavity floor was created (plane A). Plane B was parallel to plane A, but located 1.5 mm coronally. The extracted contour line of the PCD in plane A was uniformly contracted by 0.5 mm and projected onto plane B, forming an irregular cylinder-shaped space between the two planes. Therefor, the opposite PCLDW was parallel to each other, resulting in a pulp chamber extension angle of 0 degree. The dental tissues inside this space were replaced by restorative materials, and was regarded as the central retainer of the endocrown with an PCLDW height of 1.5 mm. The coronal portion above plane B combined with the central retainer constituted the endocrown, and was connected to the dental remnant with a 120-µm thick cement layer. In models A-T1.0 and A-T1.5, the modeling process was basically the same except that the contour lines of the PCD in plane A were contracted by 1.0 mm and 1.5 mm, respectively. In

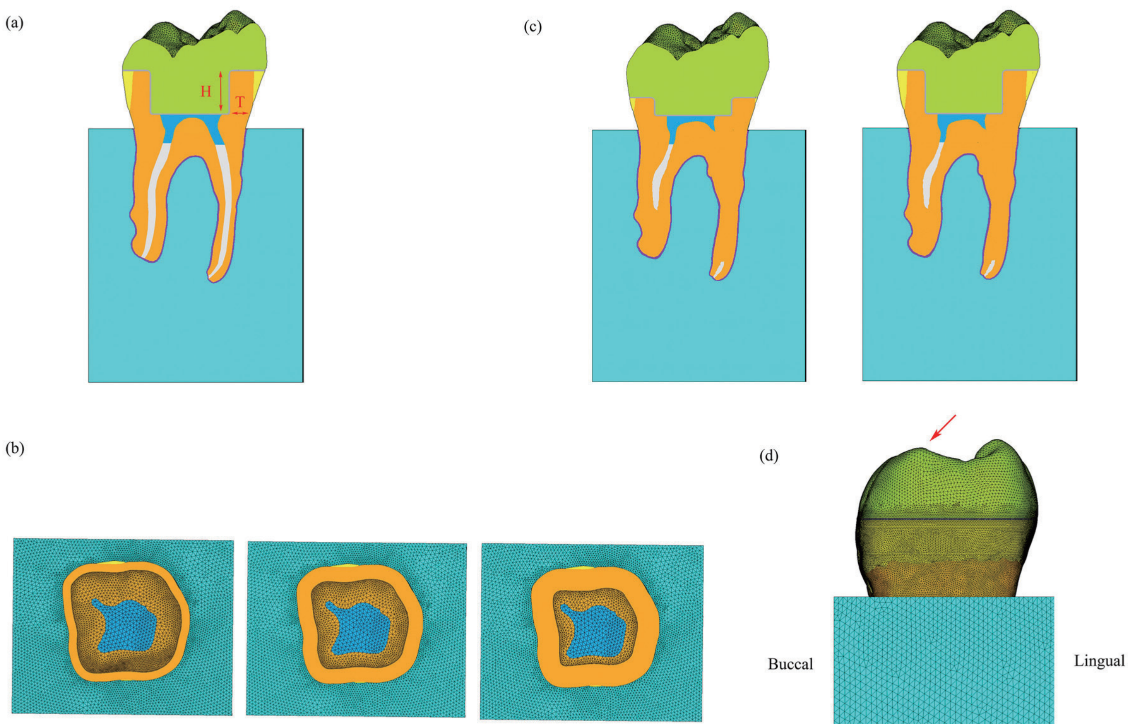

Fig. 1 (a) Schematic diagram of thickness and height of PCLDW in the coronal plane; (b) PCLDW thickness in the transverse plane; (c) PCLDW height in the coronal plane; (d) lateral load applied to the FE model.

Group B, the height of PCLDW was increased to 3.5 mm. As the location of plane A was fixed, plane B was raised to 3.5 mm. Based on the modeling steps described above, models B-T0.5, B-T1.0, and B-T1.5 were reconstructed, representing the FE models of endocrown-restored molars with PCLDW thicknesses of 0.5, 1.0 and 1.5 mm, respectively. Three types of restorative materials frequently used clinically —lithium disilicate-reinforced glass ceramic (IPS Empress 2, Ivoclar Vivadent, Schaan, Liechtenstein), zirconia-based ceramic (In-Ceram Zirconia, Vita Zahnfabrik, Bad Säckingen, Germany), and high-temperature polymerized composite resin (Lava Ultimate, 3M ESPE, St. Paul, MN, USA)— were selected in this research.

FE and Weibull analyses

The dental tissues and materials were considered to be linearly elastic, homogeneous, and isotropic. The material properties were shown in Table 1[26-37]. In addition, the adhesion between the remaining dental tissues and the endocrowns was considered to be perfect. All the nodes in the FE models at the mesial, distal, and basal surfaces of the alveolar bone were selected, and their degrees of freedom were set to 0 in the x, y, and z directions. Lateral load was considered to be more damaging than axial load[23]. In order to simulate the normal lateral masticatory force, a 250-N load with an angle of 45° to the long axis of the molar was applied to the lingual side of the buccal cusps according to previous studies[38,39]. As the FE models were set to be linear elastic, stresses under other loads (up to 1,000 N in 50-N increments) were calculated in proportion to the data for 250 N. Fractures normally originated from the coronal regions where the load was applied, propagated apically, and finally extended to the PCD around the central retainer of the endocrown[24]. Thus, the present research focused on the distribution of the maximum principal stress in the cervical region of the FE models. The stress was analyzed using Ansys software (Ansys, v16.0, Swanson Analysis, Canonsburg, PA, USA).

For the endocrown-restored molars, failure was presumed to originate from the region where the maximum principal stress occurred according to the normal stress failure criterion. Thus, a Weibull risk-of-rupture analysis was employed, and the survival probability was calculated as:

$$P_s(\sigma)=\exp[-(\sigma/\sigma_0)^m]$$

In this equation, $P_s(\sigma)$ represents the survival probability of the node at the maximum principal stress σ, while σ_0 and m represent the characteristic strength and Weibull modulus of different materials and dental tissues, respectively. For a system with n=i sources, the system's survival probability (P_s) was the product of each component's survival probability:

$$P_s=\prod_i P_{si}$$

As a result, the survival probabilities of the endocrown (P_{s1}), the cement layer (P_{s2}), and the dentin (P_{s3}) were calculated separately, and the overall failure probability (P_f) was expressed as:

$$P_f=1-P_{s1}\times P_{s2}\times P_{s3}$$

Table 1 Material properties

Material	Elastic modulus (GPa)	Poisson ratio	Characteristic strength (GPa)	Weibull modulus
Enamel	84.1	0.3	—	—
Dentin	18.6	0.3	44.5	3.4
Periodontal ligament	0.1	0.5	—	—
Alveolar bone	1.4	0.3	—	—
Gutta percha	0.1	0.4	—	—
Flowable resin	5.3	0.3	—	—
Cement layer	7.0	0.3	453.8	4.0
IPS Empress 2	103.0	0.2	231.0	5.4
In-Ceram Zirconia	242.0	0.3	541.8	10.2
Lava Ultimate	12.7	0.5	300.6	10.9

Overall failure probability versus load curves for the FE models with different PCLDW thicknesses, heights, and materials were calculated.

RESULTS

As shown in Fig. 2a, when the endocrown was made from IPS Empress 2, the maximum tensile stress (MTS) in model A-T0.5 was concentrated in both the endocrown and the dentin. In the endocrown, apart from the areas where the load was applied and the occlusal fissures, the MTS was concentrated in the regions adjacent to the mesiolingual and distolingual angles of the cavity floor. As the thickness of the PCLDW increased (models A-T1.0 and A-T1.5), the concentrated stress on the lingual side slightly increased (Fig. 2b). Because the cement layer made from low elastic modulus material was thin, thus hardly affected the process of stress transmission, the patterns of MTS distribution in the PCD around the endocrown and the cement layer were similar to that in the central retainer of the endocrown, with the stress being concentrated on the mesiolingual and distolingual angles of the cavity floor. The stress nephogram further revealed that as the PCLDW thickness increased, the MTS in the PCD around the endocrown and the cement layer slightly increased accordingly (Figs. 2c and d). With increasing PCLDW height (models B-T0.5, B-T1.0, and B-T1.5), the stress distribution and its change tendency were similar to the FE models in Group A. Fig. 3 showed that the overall failure probabilities in the IPS Empress 2 FE models were similar, regardless of the PCLDW thickness and height.

In the In-Ceram Zirconia FE models, the patterns of maximum principal stress distribution were essentially the same as those in the IPS Empress 2 models (Fig. 4). Specifically, the stresses in the central retainer of the endocrown, the PCD surrounding the endocrown, and the cement layer were concentrated in the areas adjacent to the mesiolingual and distolingual angles of the cavity floor. As the PCLDW thickness increased, the concentrated stress slightly increased. The stress distributions in the FE models in Groups A and B were similar. According to Fig. 3, the overall risks of failure in the In-Ceram Zirconia FE models were similar to those in the FE models using IPS Empress 2.

When Lava Ultimate was chosen as the restorative material, the MTS was concentrated in the endocrown and the dentin in a similar manner (Fig. 5). Although the location of the MTS concentration regions were unchanged, the stress decreased as the PCLDW thickness increased, which was contrary to the phenomena for the models depicted in Figs. 2 and 4. Compared with the FE models using IPS Empress 2 or In-Ceram Zirconia, the peak values of the MTS in the central retainer of the endocrowns were much lower in the Lava Ultimate FE models, and were higher in the PCD surrounding the endocrown (Figs. 6 and 7). The Weibull analysis revealed that the overall failure probabilities in the Lava Ultimate FE models with different PCLDW thicknesses and heights were similar, but remained higher than those for the IPS Empress 2 and In-Ceram Zirconia FE models (Fig. 3).

DISCUSSION

Although endocrowns have been considered as alternative restorations for endodontically treated posterior teeth with extensive coronal loss, the effect of PCD on the biomechanical behavior of restored teeth is not completely clear. This study found that the influence of the PCLDW thickness and height on the stress distribution and failure risk varied in endocrown-restored molars using different materials. Thus, the null hypothesis was rejected.

In recent years, lithium disilicate-reinforced glass ceramic has become one of the most frequently used

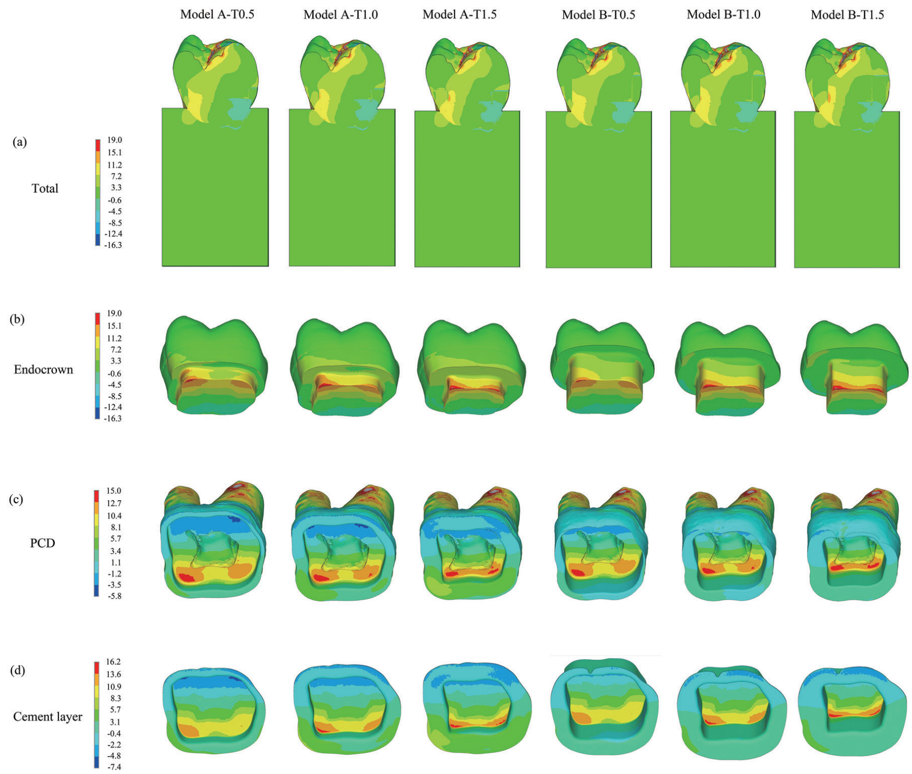

Fig. 2 Maximum principal stress (MPa) distributions in (a) restored teeth in buccolingual cross-section; (b) endocrowns; (c) PCD and (d) cement layer in IPS Empress 2 FE models.

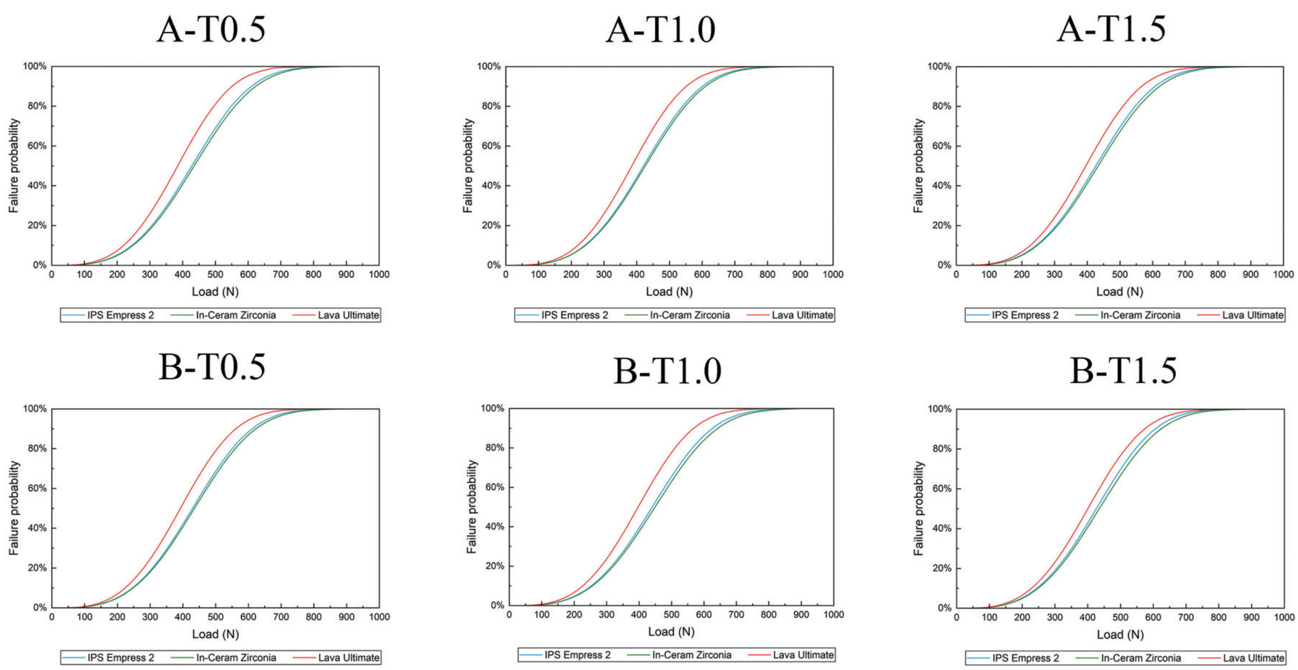

Fig. 3 Overall failure probability versus load curves of FE models with different restorative materials.

restorative materials due to its superior esthetic and functional performance. In this study, we observed that in molars restored with lithium disilicate-reinforced glass ceramic, the stress was concentrated in the regions where the load was applied and in the cervical region, indicating that tooth fracture was likely to occur at

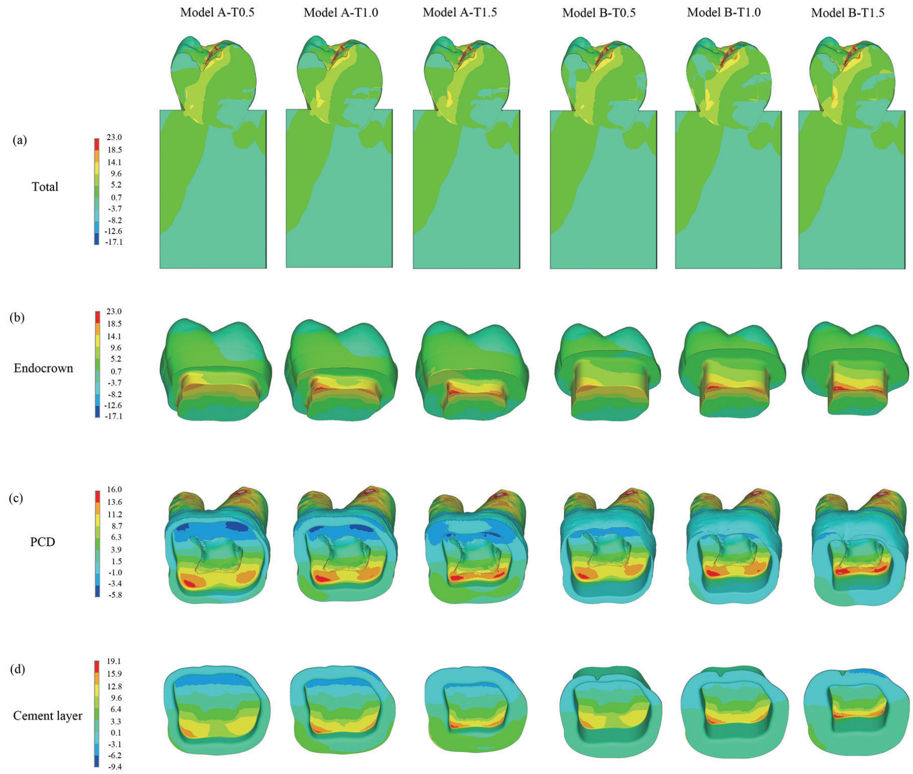

Fig. 4 Maximum principal stress (MPa) distributions in (a) restored teeth in buccolingual cross-section; (b) endocrowns; (c) PCD and (d) cement layer in In-Ceram Zirconia FE models.

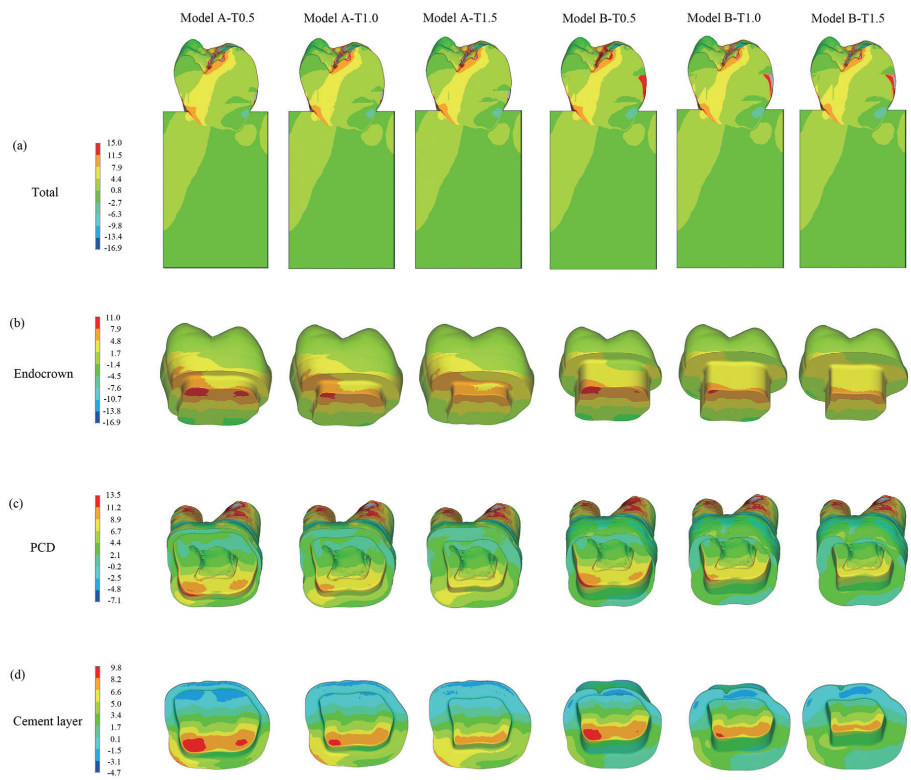

Fig. 5 Maximum principal stress (MPa) distributions in (a) restored teeth in buccolingual cross-section; (b) endocrowns; (c) PCD and (d) cement layer in Lava Ultimate FE models.

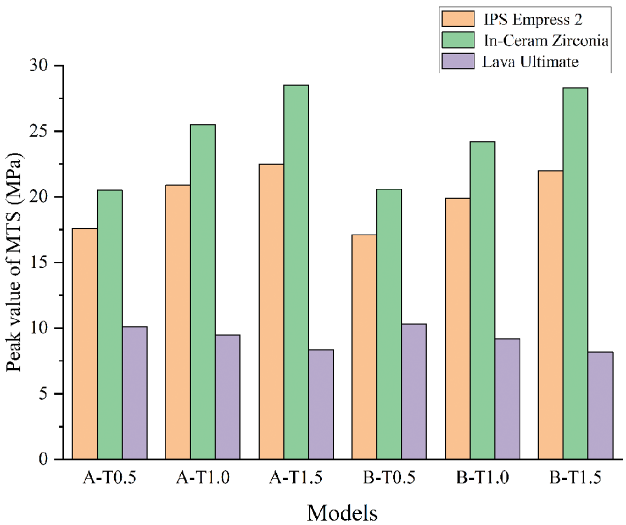

Fig. 6 Peak values of MTS in central retainer of endocrown in FE models with different materials.

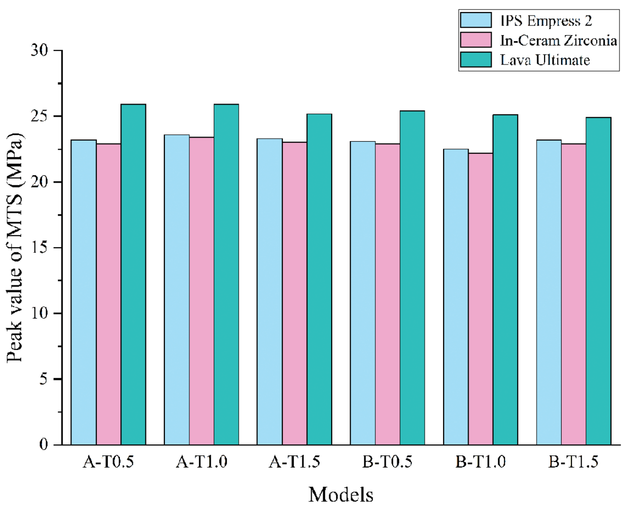

Fig. 7 Peak values of MTS in PCD in FE models with different materials.

these positions. These findings are in accordance with previous studies[24,40]. In the cervical region, the MTS on the lingual side was higher than that on the buccal side, which was understandable based on the leverage effect. Contrary to our expectations, the results further showed that the concentrated stress on the lingual side increased as the PCLDW thickness increased. This interesting phenomenon can be explained by the stress shielding effect, which is commonly observed in the field of sports medicine[41,42]. In a situation where the elastic modulus of the restorative material is much higher than that of the dentin, the endocrown is the first and major object to bear the vast majority of the energy, then the remaining energy is transferred to the tooth root with transition of the PCD. Thus, the stress in the endocrown is much higher than that in the dentin beneath it, as shown in the stress nephograms. When the thickness of the PCLDW is increased, the total mass of the endocrown made of glass ceramic with a high elastic modulus is reduced. As a result, more energy is transferred to the dental remnant, especially to the PCD around the rigid restoration, causing the stress adjacent to these regions to increase. Although the stress in the cervical region increased as the wall thickness increased, the overall failure probabilities of the restored molars were similar, indicating that the difference in stress in the restored molars with different PCLDW thicknesses was not large enough to affect the longevity. The results further revealed that not only the thickness of PCLDW, but also the height of PCLDW did not affect the long-term failure risk of endocrown-restored molars. Tribst *et al*. studied the biomechanical behavior of endocrown-restored molars with different “amount of dental remnant” and found that the PCLDW height affect the stress distribution in the restored molars[43]. However, the difference of stress distributions in the FE models was small according to the stress nephogram; furthermore, the Weibull analysis used to predict the longevity was not calculated in the previous study. *In vitro* studies also indicated that there was no significant difference in the fracture load of endocrown-restored molars with different PCLDW heights, which was consistent with our results[18,21]. So when a large amount of PCD is lost after endocrown preparation, utilization of lithium disilicate-reinforced glass ceramic can protect the remaining dental tissues through the stress shielding effect. Previous studies also found that endocrown-restored molars using lithium disilicate-reinforced glass ceramic showed satisfactory fracture resistance and clinical performance[6,23]. It is important to point out that although the quantity of remaining PCD does not affect the biomechanical behavior of restored molars, conservative treatment is still recommended in endocrown preparation. Debonding is the primary cause of endocrown failure[22], so minimal invasive preparation for endocrown can preserve more dental hard tissues and then obtain larger cementation surface area, thus decrease the risk of debonding in the future.

In clinical practice, zirconia-based ceramic is commonly used for the fabrication of traditional restorations due to its excellent fracture resistance[44]. The present results showed that in endocrown-restored molars with zirconia-based ceramic, the stress distributions and overall failure probabilities were similar to those in molars restored with lithium disilicate-reinforced glass ceramic, indicating that endocrown-restored molars using zirconia-based ceramic would have a similar reparative effect to those restored with glass ceramic theoretically. However, the adhesion between the remaining dental tissues and the endocrown was considered to be perfect in this study. Clinically, zirconia-based ceramic is much hard to be etched, consequently its bond to dentin is inferior to that of etchable ceramics, thereby weakening the stress shielding effect in the restored molars. Furthermore, the wear resistance of zirconia-based ceramic is greater than that of enamel[45], thus an endocrown made of zirconia-based ceramic that has not been finely polished could aggravate wear on the opposing teeth. Overall, zirconia-based ceramic is not an ideal material for the manufacture of endocrowns.

On account of its similar elastic modulus to dentin and favorable machinable features, high-temperature polymerized composite resin is currently considered to be a selectable material for the manufacture of prostheses. The present study revealed that for molars restored with composite resin, the overall failure probabilities were higher than those of molars restored with ceramics, predicting inferior longevity in the long term. These findings can be explained as follows: as the elastic modulus of composite resin is similar to that of dentin (12.7 GPa *vs.* 18.6 GPa), a composite resin endocrown would dissipate almost equivalent energy to the dentin beneath it per unit volume. As a result, compared with the molars restored with ceramics, the stress reduced greatly in the endocrown, and increased in the PCD surrounding it. According to the stress nephogram, the difference of stress distributions between the endocrown and the dental remnant reduced greatly in the endocrown-restored molars using composite resin. The results showed that the stress shielding phenomenon is weakened in the molars restored with composite resin, and more energy is transferred to the dental remnant, leading to an inferior biomechanical performance. Zheng *et al.* suggested that the endocrown-restored teeth using composite resin have lower failure probabilities than those using ceramics[24]. On the one hand, the failure risk of cement layer was not considered in their study; on the other hand, only the failure probabilities of FE models under the axial load were presented, the data under the lateral load was missing. Gresnigt *et al.* found that although the endocrown-restored molars using composite resin had a similar fracture strength to those restored with ceramic material under the axial load, they were significantly lower under the lateral load[46]. El Ghoul *et al.* also considered that fracture resistance of endocrown-restored molars using composite resin blocks was inferior to that of molars using ceramic materials[23], consistent with the present results.

In present study, we investigated the effect of PCLDW thickness and height on the stress distributions and failure risks of endocrown-restored molars with different materials under a static load. It should be noted, however, that teeth experience more complicated situations in the oral environment, including fatigue loads and changing temperature. Therefore, *in vitro* studies using thermal cycling mechanical loading testing method are required in order to simulate the complex oral environment. In addition, the bonding between the endocrown and the dental remnant was assumed to be perfect in this study, which is unlikely to be achieved clinically due to the limitations of the existing bonding technology and the presence of sclerotic dentin in the pulp chamber. Therefore, clinical studies related to the realistic bonding effect is warranted in the future.

CONCLUSION

Within the limitations of this study, the following conclusions can be drawn: compared to zirconia-based ceramic and high-temperature polymerized composite resin, utilization of etchable lithium disilicate-reinforced glass ceramic provides superior longevity of endocrown-restored molars due to the stress shielding effect, regardless of the thickness and height of PCLDW.

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