Journal of Dental Sciences 17 (2022) 1115—1124

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Original Article

Investigation of stress distribution within an endodontically treated tooth restored with different restorations

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Received 24 August 2021; Final revision received 21 January 2022
Available online 21 February 2022

KEYWORDS
Nonlinear finite element analysis;
Polyetheretherketone;
Restorative material;
Stress concentration;
Young's modulus

Background/purpose: Recently, metal-free restoration has become the standard in prosthetic treatment. However, it is still unclear which combination is most effective in preventing root fracture and secondary caries. The purpose of this study was to evaluate the influence of different post systems, crown materials, crown thickness and luting agents on the stress distribution around the crown margins, cervical dentin and the tip of the post.
Materials and methods: Ninety-six mandibular first premolar models were developed and analyzed using finite element analysis (FEA). Two designs of crowns, six kinds of crown materials, four types of post and core systems and two kinds of luting agents were included and evaluated for the stress distribution within the abutment teeth. The Von Mises stress magnitudes were compared among all models.
Results: The stress at the tip of the post decreased as the young's modulus of luting agent decreased; The stress concentrated more at the cervical area (dentin and crown), as the physical properties of the crown material increased.
Conclusion: Crowns fabricated using polyetheretherketone (PEEK) can reduce the stress concentration at the cervical area, so it may be possible to reduce the amount of tooth reduction during abutment tooth preparation. The stress distribution around the post tip is affected by

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https://doi.org/10.1016/j.jds.2022.01.015

the post and core systems and luting agent, regardless of crown materials and thickness. When inserting a post of the higher Young's modulus such as zirconia post, methyl methacrylate luting cement can reduce the stress concentration at the tip of the post.

Introduction

Metal-free restoration has become a standard alternative treatment option due to aesthetics and metal allergies. With the advancement in digital technologies of CAD/CAM systems, alternative esthetic restorations have been introduced. Ceramics and composite resin have been used as restorative materials using CAD/CAM systems. Polyetheretherketone (PEEK), which is a polymeric material, has been proposed for prosthetic applications, including crown restorations.[1,2] It was reported that crowns fabricated using PEEK prevent the stress concentration at the crown margin and reduce secondary caries.[3] Besides, there is also a possibility of reducing the crown's thickness.[3] It is also worth mentioning that Luting agents are the mediator to transfer and disperse the stress. The adhesive properties and Young's modulus substantially vary among different luting agents. These properties are the key factors that affect the long-term durability of dental restoration.[4]

Most commercially available esthetic and metal-free post and core systems rely on a prefabricated post reinforced with composite resin. However, there is an additional adhesive interface between the post and core, which may increase the restoration failure rate.[5] Because Young's modulus is different between the post and the core material, and stress concentration might occur and cause post-resin peeling.[6] With the help of CAD/CAM technology, a customized one-piece post-and-core has been used as an alternative to prefabricated posts. Recent studies have confirmed using such a technique for manufacturing one-piece post-and-core in nanoceramic resin, hybrid ceramics and zirconia.[7–9] However, the difference in Young's modulus among the various kinds of post materials may affect the stress distribution within the root. Besides post and core systems, there are other factors affecting stress distribution such as the type of luting agents, crown materials and crown thickness.[3,4,10–14] To date, it is still unclear which combination is most effective in preventing root fracture and secondary caries.

Therefore, the purpose of this study was to evaluate the influence of post systems, crown materials, crown thickness, luting agents on the stress distribution around the crown margins, cervical dentin, the tip of the posts, which are directly related to secondary caries and root fractures.

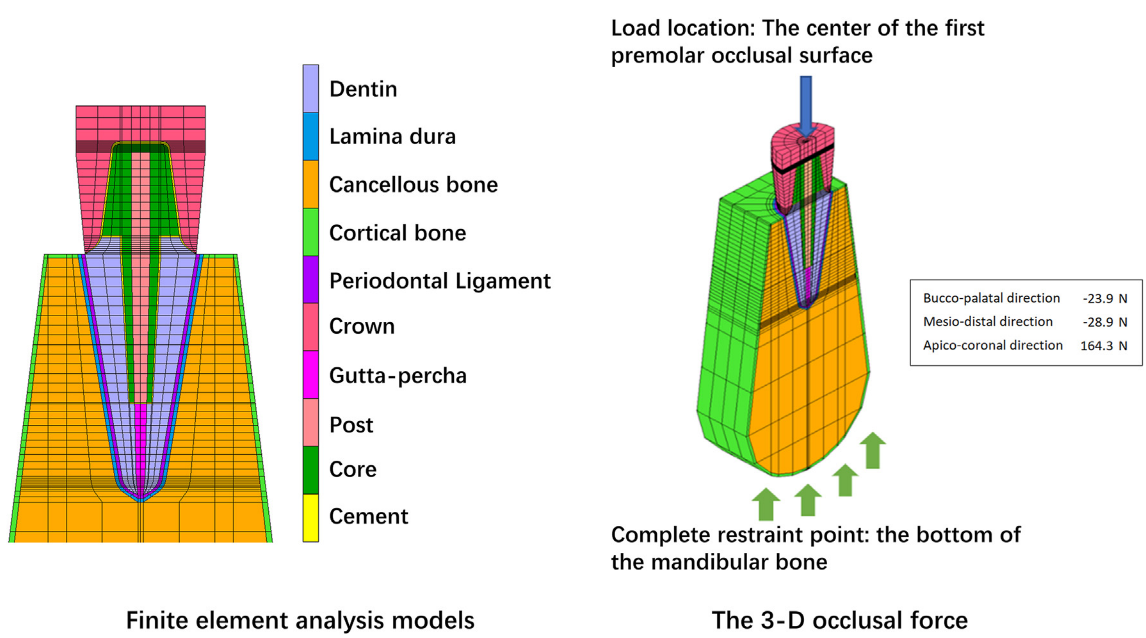

Figure 1 Details of the model. A root canal-treated mandibular first premolar model including the alveolar bone was fabricated on the personal computer. The model consisted of a crown, abutment tooth, luting agent, gutta-percha, dentin, core, post, periodontal ligament, lamina dura, cancellous bone, cortical bone; the hexahedral element was applied.

Materials and methods

Three-dimensional nonlinear finite element models were developed and analyzed using finite element analysis software (FEA) (MSC Marc Mentat2003, MSC software Corp, Santa Ana, CA. USA). Ninety-six types of first mandibular premolar models were established. In all the models, it was assumed that the subject tooth underwent endodontic treatment.

All models consisted of a crown, luting agent, core, post, dentin, gutta-percha, periodontal ligament, lamina dura, cancellous and cortical bone. The abutment tooth is a root canal treated premolar. The height and diameter of the model tooth were 18 mm and 12 mm, respectively, at the crown margin level. The apical 12 mm of the root was invested in a socket of lamia dura (0.3 mm thick) and had a uniform periodontal ligament (0.2 mm thick). In each model, dowel space was 8 mm in-depth, and the heights of core and crown were 4 mm and 6 mm, respectively (Fig. 1). The height of the ferrule was 2 mm in all models. The finish line design on this model was the round shoulder with a 0.5 mm radius and a taper of six degrees to the long axis of the tooth (normal crown model). Two types of simulated crown models were fabricated, depending on the thickness of the axial wall: one had a standard thickness of the crown, and the other had half-thickness of the crown in the axial wall. Since the axial wall of the Half crown was halved from the margin to the top of the abutment, the finished line design on the Half crown model was the chamfer (Fig. 2).

In this study, posts and cores were built with four types of materials. One was glass fiber post reinforced with composite resin (GFP)[15,16] and the others were CAD/CAM materials: nanoparticle clusters resin ceramics (LUP),[17] polymer-infiltrated ceramic network ceramics (HCP),[18] zirconia (ZRP).[19] Six types of crown materials were involved in this

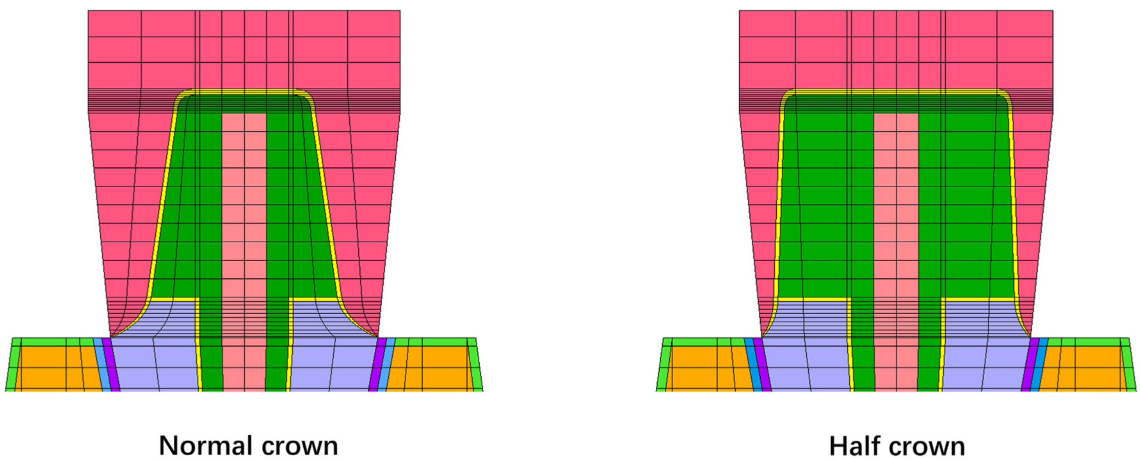

Figure 2 Normal thickness of crown and half thickness of the normal crown. Two types of crown models were fabricated depending on the thickness of the axial wall of the crown: normal crown and Half crown.

Table 1 Mechanical properties of materials.

	Young's modulus (GPa)	Poisson's ratio	References
Dentin	15.0	0.31	27
Periodontal ligament	Nonlinear	Nonlinear	26
Lamina dura	13.7	0.30	25
Cancellous bone	0.345	0.31	27
Cortical bone	13.7	0.30	25
Gutta-percha	0.00069	0.45	24
Composite resin core	12.0	0.33	16
Glass fiber post	29.2	0.30	15
Polyetheretherketone (PEEK)	4.1	0.40	20
Nanoceramic hybrid resin composite	14.8	0.30	21
Hybrid resin composite	21.0	0.27	22
Leucite-reinforced glass ceramics	64.9	0.20	23
Lithium disilicate glass ceramics	95.0	0.33	23
Zirconia	205.0	0.19	19
Nanoparticle clusters resin ceramics	11.0	0.30	17
Polymer-infiltrated ceramic network ceramics	34.7	0.28	18
Composite resin luting agent	18.0	0.30	22
Methyl methacrylate-based luting agent	4.5	0.40	14

study, namely, polyetheretherketone (PKC),[20] nanoceramic hybrid resin composite (CRC),[21] hybrid resin composite (HRC),[22] leucite-reinforced glass ceramics (IEC),[23] lithium disilicate glass ceramics (EMC),[23] zirconia (ZRC).[19] Two types of luting agents, composite resin[22] and methyl methacrylate-based luting agent[14] were used. The stress distribution of all combinations was analyzed using FEA.

In addition to this, two designs of posts and cores were included. One was made of prefabricated glass fiber post reinforced with composite resin core (GFP), and the other was a one-piece custom post and core (LUP, HCP, ZRP). It was assumed that the crown was cemented. Each element was assigned a unique elastic property to represent the modeled materials (Table 1).[14–27] Except for the periodontal ligament, homogeneity, isotropy, and liner elasticity were assumed for all materials. A nonlinear elastic property was assigned to the periodontal ligament because of its viscoelastic properties.

In these models, the bottom of the mandibular bone was restricted entirely. The three-dimensional chewing force was shown in Fig. 1.[11] It was measured with a small three-dimensional occlusal force meter during chewing beef jerky. It was applied to the central node of the occlusal surface of the first premolar. In this study, the Von Mises stress magnitudes at the crown margin, cervical dentin, and the tip of the post were compared for the ninety-six models (Fig. 3).

Results

The stress distribution of the abutment teeth and crowns in the sagittal cross-section view is shown in Fig. 4. Stress

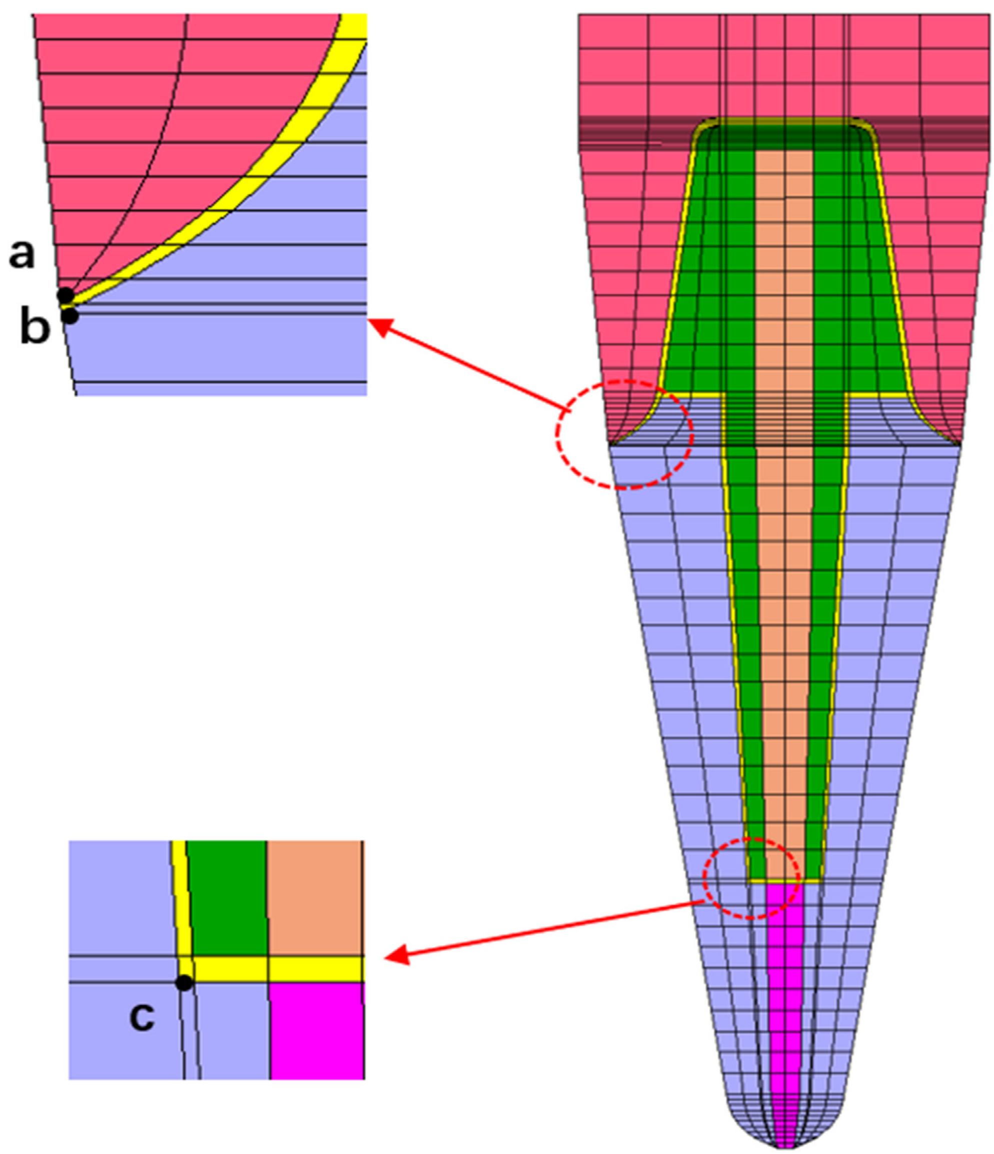

Figure 3 Analysis points. The three analysis points: crown (a), dentin (b) around the crown margin of the first premolar and dentin (c) around the tip of the post.

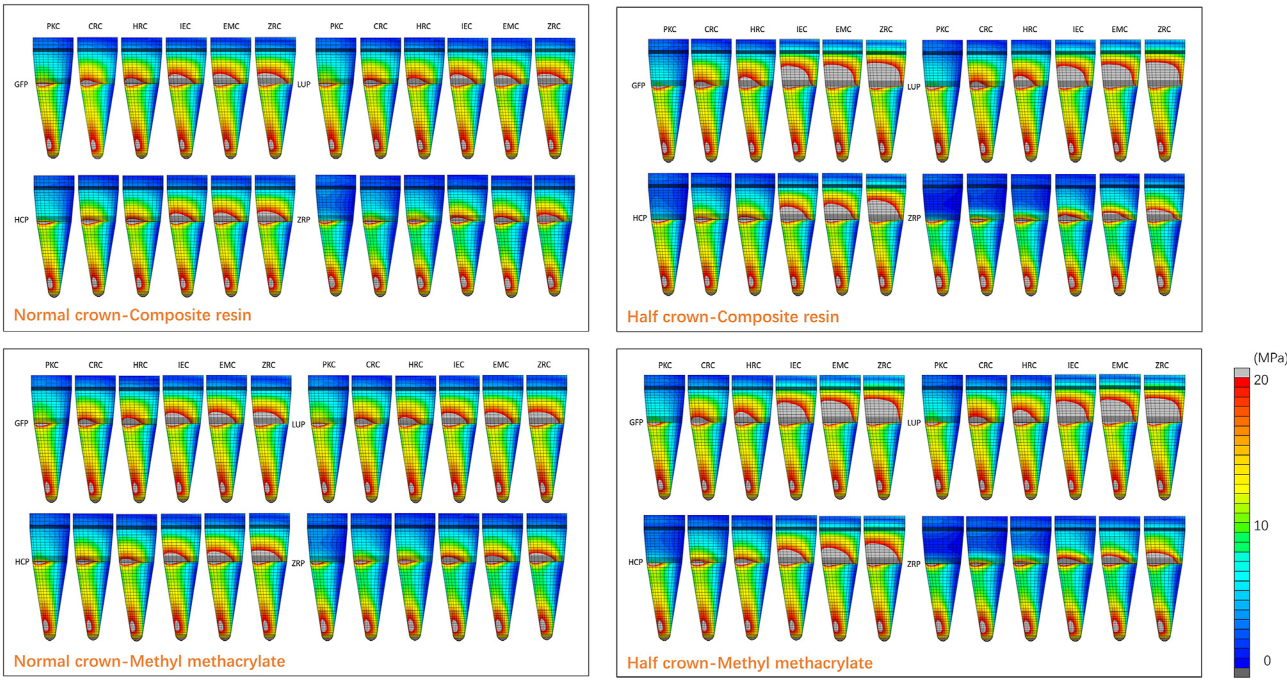

Figure 4 Stress distribution within the abutment teeth and crowns (frontal plane). The equivalent stress distribution in a buccolingual cross-section of the abutment tooth in different combinations of crown, post and cement. Gray and red represent the high stress concentration area as indicated by the color legend. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

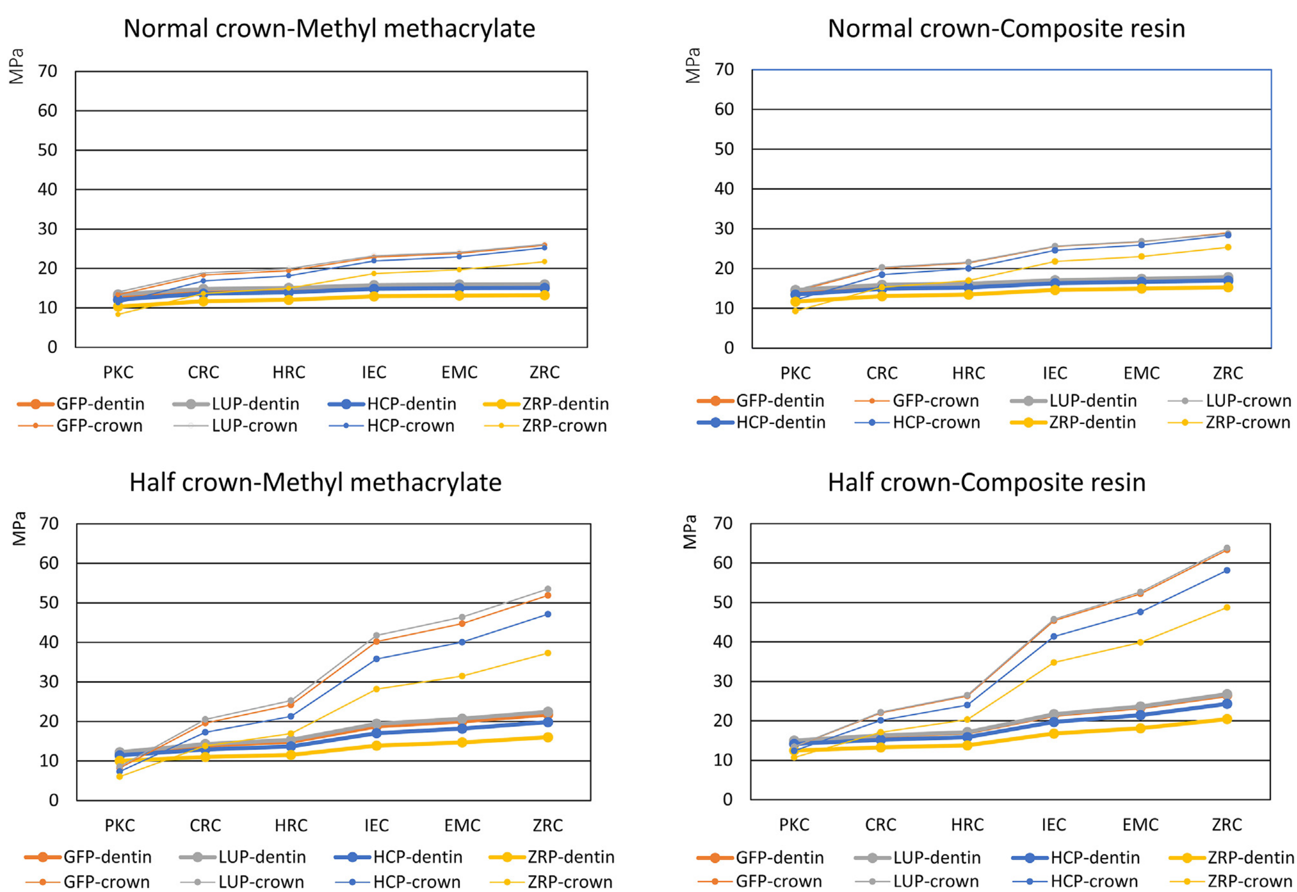

Figure 5 Stress value at the crown margin and the cervical dentin.

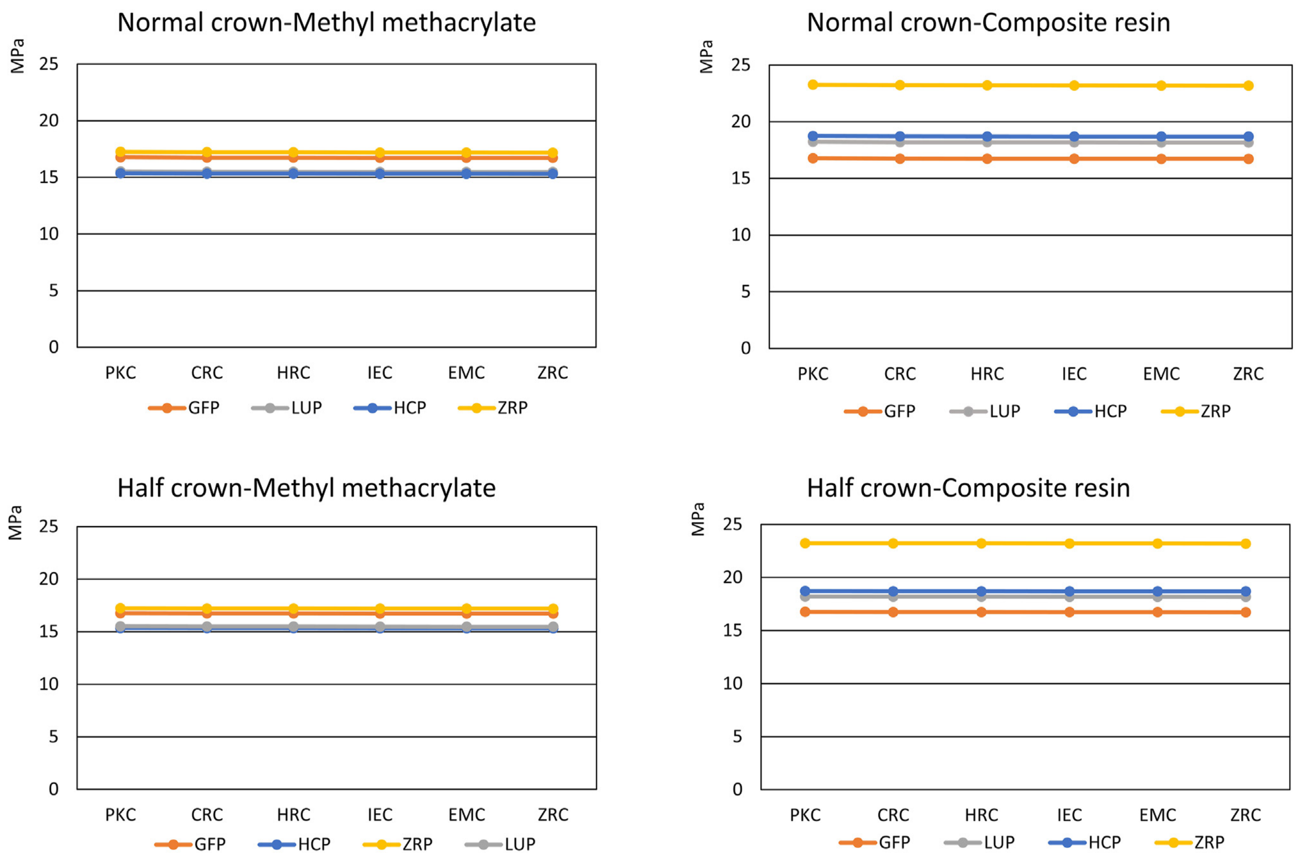

Figure 6 Stress value at the tip of the post.

distribution at the crown margin and the cervical dentin is shown in Fig. 5, and Fig. 6 shows the stress distribution within the dentin at the tip of the post. The stress magnitude at each analysis point is shown in Table 2.

As shown in Fig. 4, the stress distribution in all models was mainly concentrated at the post apices and the cervical area of the abutment tooth. Neither the crown material nor thickness changed the concentration areas at the post apices (Fig. 6). Types and thickness of crown had little effect on stress distribution at the tip of post. The stress at the tip of the post decreased with reducing Young's modulus of luting agent. When methyl methacrylate was used, the stress value was as the following: ZRP $>$ GFP $>$ LUP $>$ HCP. On the other hand, when composite resin was used, the stress was ZRP $>>$ HCP $>$ LUP $>$ GFP. The stress value in ZRP was the largest among all groups.

The stress value in methyl methacrylate-based luting agent was lower than that in composite resin luting agent among all groups (Fig. 5 and Table 2). The larger Young's modulus of the crown, the greater the stress value within dentin and crown at the cervical area. Also, the degree of increase in stress was more significant in the crown than in the dentin. The stress difference between dentin and crown in each group varies with the crown material. Specifically, the stress was highest for ZRC and lowest for PKC. Comparing the models with two different thicknesses, the slope of the stress curve in the Half crown was more significant than in the Normal crown, which means the stress value increased more extensively in the Half crown. PKC had the smallest stress value at the cervical area (dentin or crown) among all groups. The stress magnitude of PKC in the Half crown showed less stress concentration at the crown margin than that at cervical dentin.

Discussion

Previous finite element analyses[28,29] were performed based on linear analysis methods. Although the periodontal ligament had viscoelastic properties,[26] It might significantly influence the stress distribution within the root. Therefore, a nonlinear analysis was performed in this study.

Fracture strength tests used to determine fracture resistance are essential means of analyzing the biomechanical behavior of the tooth.[30] However, they have limitations in obtaining information on the internal behavior of the tooth-restoration complex. Using FEA, a non-destructive methodology, any cross-sectional plane can be observed and the stress magnitude at any analysis point can be evaluated. FEA has been used extensively to predict the biomechanical performance of various dental restoration.[3,4,11,12,24,31] In this research, hand-made finite element models were fabricated

Table 2 Stress value in MPa at each analysis point.

Normal crown	Post and core systems	Crown materials	Stress value		
			Tip of the post	Cervical dentin	Crown margin
Methyl methacrylate	[a]GFP	[e]PKC	16.8	13.1	13.3
		[f]CRC	16.7	14.4	18.3
		[g]HRC	16.7	14.7	19.5
		[h]IEC	16.7	15.5	22.9
		[i]EMC	16.7	15.7	23.8
		[j]ZRC	16.7	15.7	25.9
	[b]LUP	PKC	15.5	13.4	14.0
		CRC	15.5	14.8	18.9
		HRC	15.5	15.1	19.9
		IEC	15.5	15.8	23.2
		EMC	15.5	15.9	24.1
		ZRC	15.5	16.0	26.1
	[c]HCP	PKC	15.4	12.1	11.3
		CRC	15.3	13.6	16.8
		HRC	15.3	14.0	18.1
		IEC	15.3	14.8	21.9
		EMC	15.3	15.0	22.9
		ZRC	15.3	15.1	25.2
	[d]ZRP	PKC	17.3	10.3	8.3
		CRC	17.2	11.7	13.6
		HRC	17.2	12.0	15.0
		IEC	17.2	12.9	18.7
		EMC	17.2	13.1	19.7
		ZRC	17.2	13.2	21.7
Composite resin	GFP	PKC	16.8	14.5	14.3
		CRC	16.7	15.8	20.1
		HRC	16.7	16.1	21.4
		IEC	16.7	17.0	25.5
		EMC	16.7	17.4	26.7
		ZRC	16.7	17.6	29.0
	LUP	PKC	18.2	14.6	14.6
		CRC	18.2	15.9	20.3
		HRC	18.2	16.2	21.6
		IEC	18.2	17.1	25.6
		EMC	18.2	17.4	26.8
		ZRC	18.2	17.9	28.8
	HCP	PKC	18.7	13.5	12.1
		CRC	18.7	14.9	18.5
		HRC	18.7	15.3	20.0
		IEC	18.7	16.3	24.6
		EMC	18.7	16.7	25.9
		ZRC	18.7	17.0	28.4
	ZRP	PKC	23.3	11.7	9.3
		CRC	23.2	13.1	15.3
		HRC	23.2	13.5	17.0
		IEC	23.2	14.6	21.8
		EMC	23.2	15.0	23.0
		ZRC	23.2	15.3	25.3
					MPa

Half crown	Post and core systems	Crown materials	Stress value		
			Tip of the post	Cervical dentin	Crown margin
Methyl methacrylate	GFP	PKC	16.8	12.0	8.2
		CRC	16.7	13.9	19.6
		HRC	16.7	14.9	24.2
		IEC	16.7	18.8	40.2

(*continued on next page*)

Table 2 (*continued*)

Half crown	Post and core systems	Crown materials	Stress value		
			Tip of the post	Cervical dentin	Crown margin
		EMC	16.7	20.0	44.8
		ZRC	16.7	21.7	51.9
	LUP	PKC	15.5	12.2	8.6
		CRC	15.5	14.3	20.5
		HRC	15.5	15.3	25.3
		IEC	15.5	19.4	41.8
		EMC	15.5	20.7	46.4
		ZRC	15.5	22.4	53.5
	HCP	PKC	15.3	11.4	7.4
		CRC	15.3	12.9	17.3
		HRC	15.3	13.7	21.3
		IEC	15.3	17.1	35.8
		EMC	15.3	18.2	40.1
		ZRC	15.3	19.9	47.1
	ZRP	PKC	17.2	10.0	6.1
		CRC	17.2	11.0	13.8
		HRC	17.2	11.6	17.0
		IEC	17.2	13.9	28.2
		EMC	17.2	14.7	31.5
		ZRC	17.2	16.0	37.3
Composite resin	GFP	PKC	16.8	14.9	13.4
		CRC	16.7	16.2	22.0
		HRC	16.7	17.0	26.3
		IEC	16.7	21.5	45.4
		EMC	16.7	23.4	52.2
		ZRC	16.7	26.5	63.3
	LUP	PKC	18.2	15.0	13.5
		CRC	18.2	16.3	22.2
		HRC	18.2	17.1	26.5
		IEC	18.2	21.7	45.7
		EMC	18.2	23.7	52.7
		ZRC	18.2	26.8	63.8
	HCP	PKC	18.7	14.2	12.4
		CRC	18.7	15.2	20.1
		HRC	18.7	15.9	24.0
		IEC	18.7	19.7	41.4
		EMC	18.7	21.5	47.6
		ZRC	18.7	24.3	58.2
	ZRP	PKC	23.2	12.5	10.7
		CRC	23.2	13.3	17.1
		HRC	23.2	13.8	20.3
		IEC	23.2	16.8	34.8
		EMC	23.2	18.1	39.9
		ZRC	23.2	20.4	48.8
					MPa

[a] GFP: glass fiber post reinforced with composite resin.
[b] LUP: nanoparticle clusters resin ceramics.
[c] HCP: polymer-infiltrated ceramic network ceramics.
[d] ZRP: zirconia post.
[e] PKC: polyetheretherketone.
[f] CRC: nanoceramic hybrid resin composite.
[g] HRC: hybrid resin composite.
[h] IEC: leucite-reinforced glass ceramics.
[i] EMC: lithium disilicate glass ceramics.
[j] ZRC: zirconia crown.

based on the requirements of the experiment. However, it was difficult to simulate the morphology of the actual root canal and rebuild the tooth shape with cusps, ridges, and grooves on the occlusal surface.[3] Prior to considering the complexity of the model shape, the primary purpose of this study is to evaluate the effect of various material properties and crown thickness on stress distribution within the abutment. The Von Mises stress was used to calculate the stress value due to an excellent estimate of the material's actual failure stress under multi-directional shear, tension, and compression loading. The Von Mises stress tends to be reliable in estimating the possibility of failure.[29,31,32]

This study focuses on analyzing the stress concentration at the cervical area and the tip of the post. Stress concentration at the cervical area of teeth collapses the interfacial luting agents of the crown and result in microfracture in the dentin. Ultimately, it leads to an increased risk of non-carious cervical lesions and secondary caries progression.[13,33,34] Suzuki; et al. suggested that high stress generated around the tip of the post caused an increased chance of fatal vertical root fracture.[14] The failure occurs by a process involving nucleation of crack, slow propagation of the crack, and finally catastrophic failure of the system. Therefore, every effort should be made to reduce the stress at the cervical area and the tip of the post, thereby increasing the success rate of endodontically treated teeth.

The stress concentration is significantly affected by the type of luting agent, post and core system, the thickness of crown and crown material.[3,4,11,12,14,35] For models with the same crown thickness, luting agent, and post system, the stress values at the cervical area (dentin and crown) were PKC, CRC, HRC, IEC, EMC, ZRC in ascending order. This order coincided with Young's modulus of the crown. Results showed the stress value in PKC was recorded as minimal and that of PKC-methyl methacrylate within the Half crown was lower than that within the Normal crown regardless of post systems (Table 2 and Fig. 5). Thus, it is suggested that crowns fabricated by PEEK can prevent the stress concentration at the crown margin and cervical dentin and it could allow a reduction in the axial wall of the tooth preparation. These results were supported by similar findings in the literature for such materials.[3,36] According to Mahmoudi M, Young's modulus and mechanical properties of the materials have a significant impact on the transmission and distribution of stress.[37] As PEEK has a lower Young's modulus and higher flexibility than zirconia, lithium disilicate glass ceramics, leucite reinforced glass ceramics, hybrid composite resin, and resin composite, indicating a high capability to absorb destructive fracture energy elastically.[38] Crown materials with lower Young's modulus allow more absorption of functional stresses by deformation and provide a cushioning effect reducing stress transferred to the abutment teeth.[39,40]

In comparing crown thickness, the stress value around the crown margin of the Half crown was significantly larger than the normal crown in the case of IEC, EMC, ZEC except for PKC (Table 2). But the stress value increase of CRC and HBC is not significant enough. In addition, PKC within the Half crown showed lesser stress concentration around the crown margin than cervical dentin, which indicates that luting agents need a higher level of adhesion to the crown than to the dentin. A decrease in the tooth reduction in the axial wall is not recommended when IEC, EMC, ZEC is used because it leads to an increase of stress in the cervical area.

As for the assumption of perfect bonding, interface imperfections are usually randomly distributed and they affect stress distribution in localized areas. As a consequence, imperfect bonding was not considered in order to compare the restoration system. Among all groups, the stress value around the cervical and apex region in methyl methacrylate was lower than that in composite resin except for the apex area in GFP. It reveals that methyl methacrylate with its lower Young's modulus could reduce the stress concentration at the cervical area and post apex. The GFP group was clinically commonly used in a direct method, so the adhesive material in the root canal was constant, and Young's modulus was consistent with the composite resin. Therefore, the stress value at the tip of the GFP post remained the same both in methyl methacrylate and in composite resin.

Post systems affect the stress concentration in the cervical area and post apex. The stress value in the cervical area decreases as Young's modulus of the crown increases, impairing stress transmission to the cervical dentin. In composite resin, the stress value at the tip of the post was ZRP $>>$ HCP $>$ LUP (Fig. 6) and it increased as Young's modulus of the post increased, which is in agreement with the previous study.[11] However, in methyl methacrylate, the order of the stress value was ZRP $>$ LUP $>$ HCP. It dramatically alleviates the stress concentration caused by ZRP. This observation concludes that the more rigid posts are, the lesser the rigidity of the cementing medium is recommended.[30]

Crowns fabricated by PEEK can reduce the stress concentration at the cervical area and even possibly require less tooth reduction during abutment preparation. The stress distribution around the tip of the post is affected by the post systems and luting agent type, regardless of crown materials and thickness. When inserting posts of high Young's modulus such as ZRP, methyl methacrylate acts as a stress buffer and it can reduce the stress concentration at the tip of the post.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

Acknowledgment

This study was partly supported by Grants-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (JSPS No. 16K11587, No. 21K09973, No. 16K20490).

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