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Investigation of Stress Distribution in Roots Restored with Different Crown Materials and Luting Agents

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The purpose of this study was to identify crown materials and luting agents that would decrease the stress concentrated at the roots of endodontically treated teeth. To this end, natural tooth model (NT), full cast crown model (gold-silver-palladium alloy; MC), polymer-based restorative material crown model (HCC), and all-ceramic crown model (ACC) were constructed. In each model, methyl methacrylate-based resin cement (MMA) and composite cement (CC) were used as luting agents. The magnitudes of von Mises stress of the roots during function were compared. When the luting agent was changed from MMA to CC, von Mises stress in the cervical area decreased by 37.8 % for MC, 27.1 % for HCC, and 37.0 % for ACC. Within the limitations of this study, the combination of HCC and CC gave rise to the lowest stress concentration at the cervical area.

Keywords: Nonlinear finite element analysis, Young's modulus, Von Mises stress

INTRODUCTION

Cast posts and cores have conventionally been used after endodontic treatment. This is because they are superior in mechanical strength compared to other post and core systems, especially against composite resin cores[1,2]. However, cast posts and cores may cause vertical root fracture. Moreover, in most cases, re-restoration is difficult, resulting in tooth extraction. Consequently, glass fiber posts with Young's modulus similar to dentin, as opposed to metal posts, have been used with composite resin cores[3-6]. It is hypothesized that this kind of post and core system disperses stress along the post and decreases the possibility of vertical root fracture. On the other hand, stress is concentrated at the cervical area and this stress concentration will lead to horizontal root fracture[4].

For crown materials, ceramic or polymer-based restorative materials are more frequently used. This is because these crown materials are superior to other crown materials in the following aspects: less release of metallic ions, color stability at marginal gingiva, and reproducibility of color[7-10]. Moreover, with improvement in material properties of ceramic and polymer-based restorative materials, these materials have sometimes been used as the definitive restoration material instead of the dental alloy, even in the posterior region.

For luting cements, a study conducted by Junge *et al.*[11] had cast crowns cemented with three different luting agents — zinc phosphate cement, resin-modified glass ionomer cement, and resin cement. Cyclic loading was then applied to compromised teeth restored with cast posts and cores with these cast crowns. They reported that the cast crown luted with resin cement required the highest number of load cycles before preliminary failure occurred. From this report, it was found that the resin cement had superior dentin adhesive property and tensile strength, and that it offered resistance against a high number of load cycles.

Typically, a restoration is fabricated with three material systems — post and core, luting agent, and crown. However, their interactions during function have not been thoroughly researched. It is not yet known how the various types of crown materials and luting agents, in combination with composite resin cores, will influence stress distribution in roots during function.

Loading tests[8,12,13], photoelastic analyses[14,15], and finite element methods[6,16-18] have been used to examine root fractures. Each method has its own suite of advantages and disadvantages. Although loading tests can measure failure load and mode, they cannot analyze stress distribution. Photoelastic analyses allow stress distribution to be observed in three-dimensional mode, but it is difficult to accurately analyze the magnitude of internal stress in teeth. Finite element analyses have been used for many investigations, because they can reproduce structures of various shapes of teeth with many elements defined with specific Young's modulus and Poisson's ratio values. In this manner, the distribution and magnitude of stress at any point in a root can be precisely analyzed.

In this study, a small three-dimensional occlusal force sensor with strain gages was used to measure the direction and amount of occlusal force. These values were then applied to a finite element model. In addition, nonlinear finite element models for biological tissues and structures were developed and used to analyze which types of crown material and luting agent would decrease stress concentration in teeth restored with a composite resin core and a glass fiber post.

MATERIALS AND METHODS

Occlusal force measurement device

Figure 1 shows the occlusal force measurement device used in this study. It was a small, handmade, three-dimensional occlusal force sensor[19,20] which used eight strain gages (KFR-02-120-C-1-16N10C2, Kyowa Co., Tokyo, Japan). This sensor was made of stainless steel SUS 304, consisted of two-tiered parallel plates, and the central part of the sensor had two rectangular cavities. The parallel plates were superposed at an angle of 90° to each other. This sensor was structured in this manner to the end of measuring multi-axial force accurately. As a result, large strain might be obtained by concentrating the deformation in the direction to which the occlusal force was applied, and the bite force in each direction could be detected separately without interference.

A total of eight strain gages were used, with two strain gages attached to each plate. Gage resistance and gage factor were 120 Ω and about 2.0 respectively. Strain was detected by the strain gages attached to the parallel plates. Outputs from these strain gages were passed through eight Wheatstone bridges to eight strain amplifiers (AS1203, NEC, Tokyo, Japan) and converted into output voltages.

Occlusal force measurement setup

The small, three-dimensional occlusal force sensor was set in a metal core which was made of platinum-gold alloy (Casting Gold M.C. Type IV, GC Corp., Aichi, Japan). It could detect coronoapical, mesiodistal, and buccopalatal occlusal forces separately.

The subject was a 30-year-old Japanese man with no symptoms of stomatognathic disorder, and the subject tooth was maxillary left first molar. First, the subject's endodontically treated tooth was

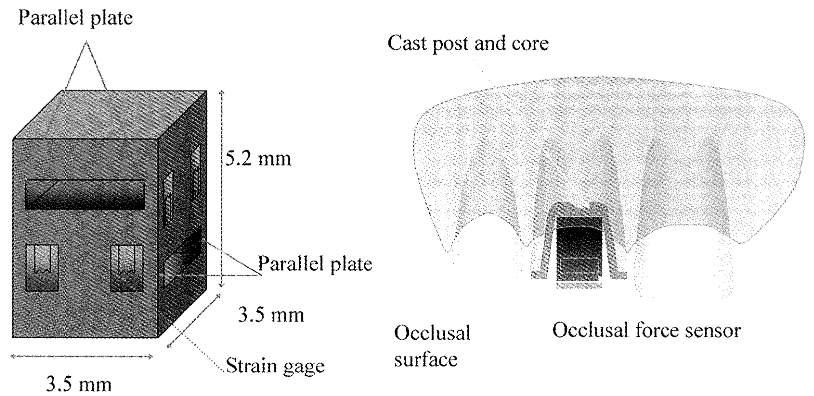

Fig. 1 The small, three-dimensional occlusal force sensor[19,20].

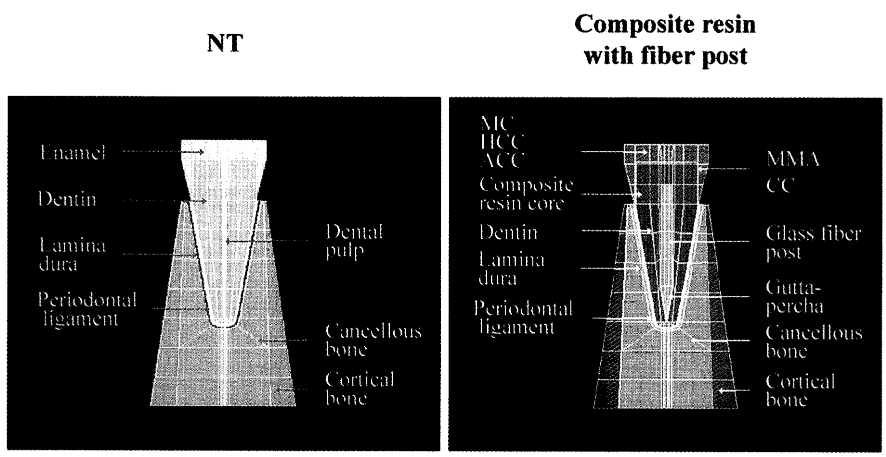

Fig. 2 Finite element analysis models, where NT: natural tooth model; MC: full cast crown model; HCC: polymer-based restorative material crown model; ACC: all-ceramic crown model; MMA: methyl methacrylate-based resin cement; CC: composite cement.

prepared with a conventional method for a post and core. Then, an impression was made with hydrophilic vinyl polysiloxane impression material (Exafine, GC Corp., Aichi, Japan), and a metal post and core (Casting Gold M.C. Type IV, GC Corp., Aichi, Japan) with the three-dimensional occlusal force sensor was fabricated. This post and core was cemented in the abutment tooth using provisional cement (Freegenol Temporary Pack, GC Corp., Aichi, Japan). An experimental occlusal surface was made of a metal frame with 0.5 mm thickness (Casting Gold M.C. Type IV, GC Corp., Aichi, Japan). Test food was a 5×5 mm piece of beef jerky (Beef Steak Jerky, Suzusho Ltd., Tokyo, Japan). The occlusal force applied to tooth during beef jerky mastication was measured with this small sensor (Fig. 1).

Nonlinear finite element models

Three-dimensional, nonlinear finite element models were developed and analyzed using a finite element analysis software (MSC.Marc Mentat 2003, MSC Software, Santa Ana, CA, USA). In this study, four such models were developed: a natural tooth model (NT), a full cast crown model (gold-silver-palladium alloy; MC), a polymer-based restorative material crown model (HCC), and an all-ceramic (dental

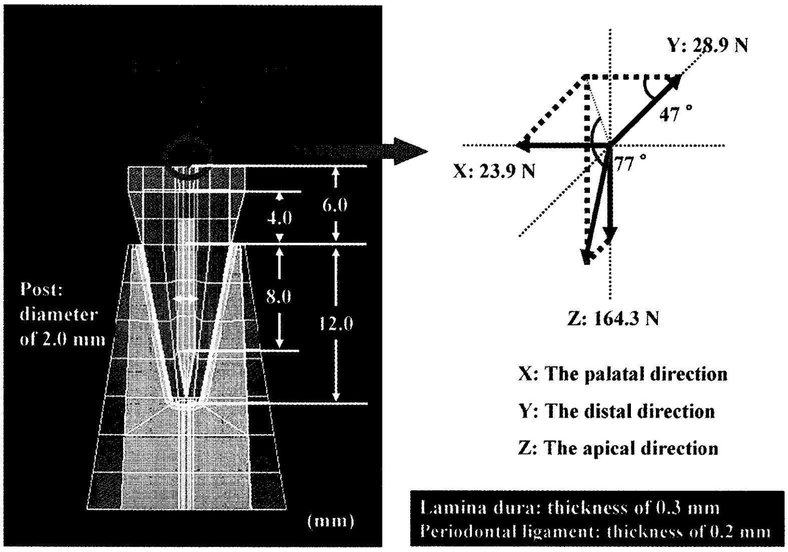

Fig. 3 The dimensions and elements of the complete model with loading vectors.

Table 1 Mechanical properties of materials

	Young's modulus (MPa)	Poisson's ratio
Enamel[21]	80000	0.30
Dentin[21]	15000	0.31
Dental pulp[22]	2	0.45
Periodontal ligament[23]	Nonlinear elastic	Nonlinear elastic
Lamina dura[24]	13700	0.30
Cancellous bone[21]	345	0.31
Cortical bone[24]	13700	0.30
Gutta-percha[25]	0.69	0.45
Composite resin cores[26]	12000	0.33
Glass fiber post[8]	29200	0.30
MC[27]	86000	0.33
HCC[28]	21000	0.27
ACC[7]	80000	0.30
MMA[29]	4500	0.40
CC[28]	18000	0.30

Abbreviations as in Fig. 2

ceramic) crown model (ACC) (Fig. 2). For the three restorative models, it was assumed that the post and core system was a composite resin core and a glass fiber post after endodontic treatment. Restored tooth was 18 mm long with a diameter of 6 mm at the crown margin level. The apical 12 mm of the root was modeled as invested in a socket of lamina dura 0.3 mm thick and had a uniform periodontal ligament thickness of 0.2 mm (Fig. 3). The remaining bone was modeled as cancellous bone and cortical bone.

Each element was assigned unique elastic properties to represent the modeled materials (Table 1)[7,8,21-29]. Homogeneity, isotropy, and linear elasticity except for the periodontal ligament were assumed for all materials, including continuous interfaces between materials. The model was restrained at all nodes on the bottom surface of the cortical bone and cancellous bone. In the NT model, the number of elements and nodes were 2080 and 2091 respectively. For the three restorative models, the number of elements was 2380 and the number of nodes was 2961.

In each model, methyl methacrylate-based resin cement (MMA) and composite cement (CC) were used as luting agents for the crowns. Thickness of luting agent was 50 μm, except for the maxillary surface of the core where thickness was 100 μm. A nonlinear elastic property was applied to the periodontal ligament[23] because it has viscoelastic properties[30] (Fig. 4). The approximate function for periodontal ligament used in this study was adapted from a previous research[23].

Occlusal force during beef jerky mastication which was measured with the three-dimensional occlusal force sensor. Force was applied to a node located at the center of occlusal surface. Stress produced in the dentin of each root was calculated as von Mises stress, and stress distribution in the root was analyzed. Magnitude of von Mises stress in the cervical surface, tip of the post, and apex of the root were then compared (Figs. 5 and 6).

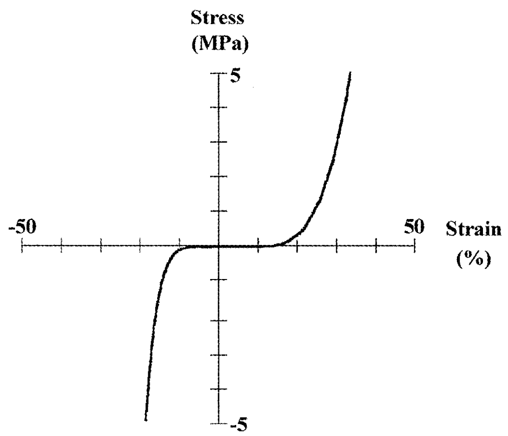

Fig. 4 Material property of periodontal ligament[23].

RESULTS

The three-dimensional occlusal force sensor measured the occlusal force applied to tooth during beef jerky mastication. It was found that the direction of occlusal force during mastication was in the disto-palatal-apical direction. Occlusal forces in the palatal, distal, and apical directions were 23.9 N, 28.9 N, and 164.3 N respectively (Fig. 3). The force was applied to the center of the occlusal surface in each finite element model, and then the von Mises stress was analyzed (Table 2).

Figures 5 and 6 show the distributions of von Mises stress. There were no differences in the magnitude of von Mises stress around the tip of the post and apex of the root among the models. In other words, different combinations of crown materials and luting agents did not affect the magnitude of von Mises stress around the tip of the post and apex of the root. On the contrary, there were differences in the magnitude of von Mises stress in the cervical area among the models. In other words, different combinations of crown materials and luting agents affected the magnitude of von Mises stress in the cervical area.

Table 2 Magnitudes of von Mises stress at each analysis point by finite element analysis (MPa)

	NT	MMA			CC		
		MC	HCC	ACC	MC	HCC	ACC
Cervical area	6.2	23.0	18.1	22.7	14.3	13.2	14.3
Tip of post	10.6	8.7	8.8	8.7	8.7	8.8	8.7
Apex area	11.6	13.7	13.7	13.7	13.7	13.7	13.7

Abbreviations as in Figs. 5 and 6.

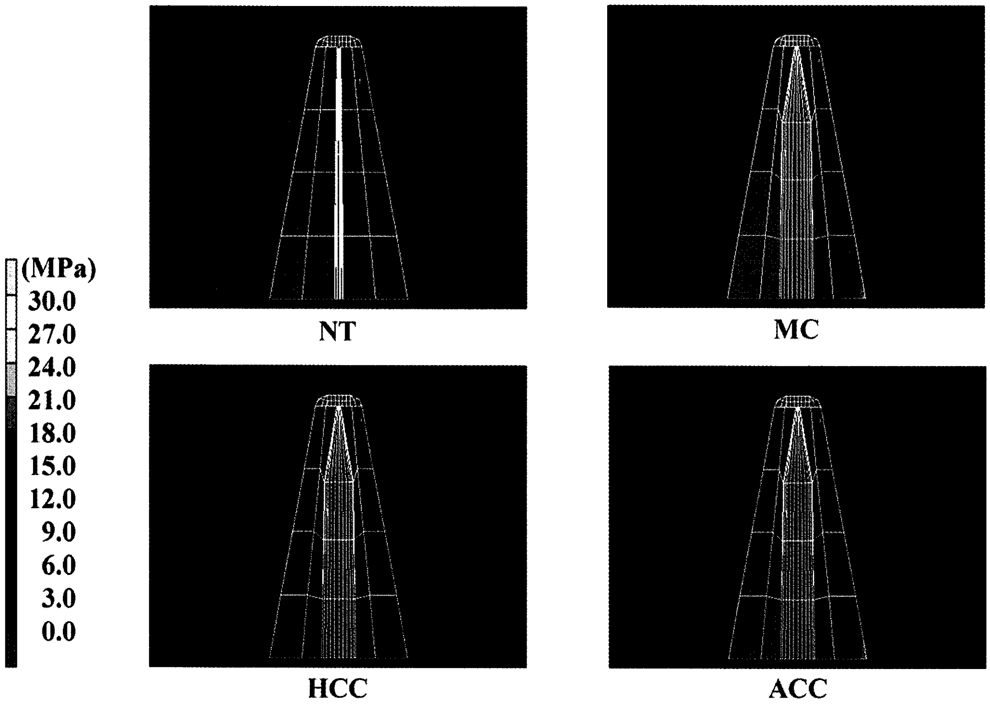

Fig. 5 Comparison of von Mises stress distributions in root for different kinds of crown materials (MC, ACC, and HCC) in frontal plane (MMA). In all models, stress was concentrated in the cervical area.

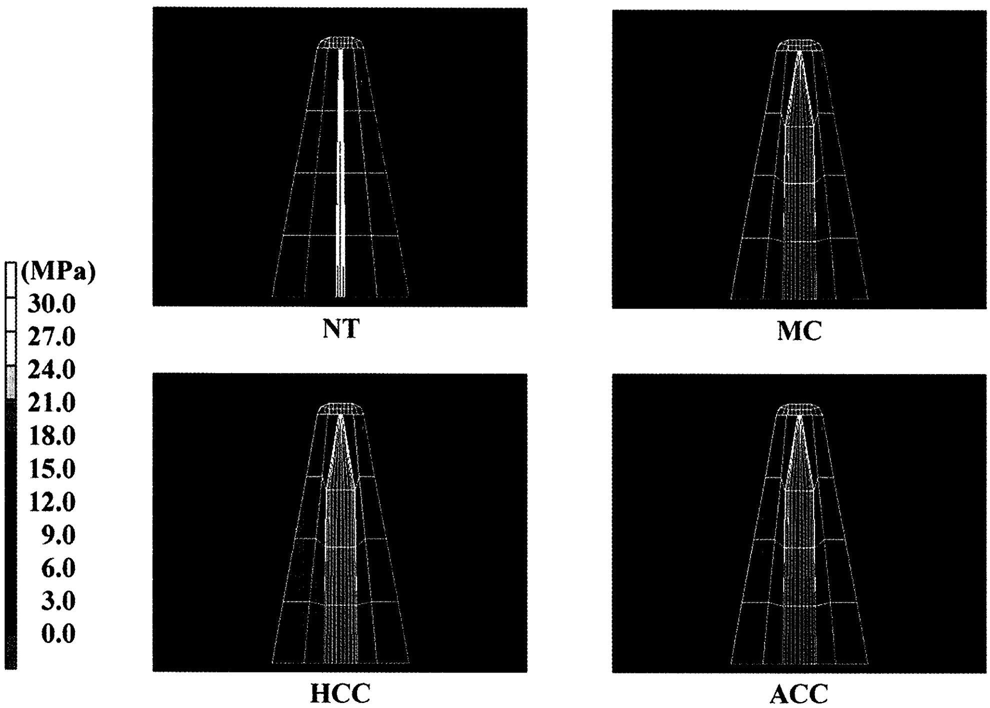

Fig. 6 Comparison of von Mises stress distributions in root for different kinds of crown materials (MC, ACC, and HCC) in frontal plane (CC). In all models, stress was concentrated in the cervical area.

DISCUSSION

Previous finite element analyses were not performed with *in vivo* measurement of occlusal force[6,16,17]. An outstanding advantage of this method is that load and direction during function *in vivo* could be reproduced in finite element models. In this study, the finite element models assumed a simple root shape, although the actual shape was not so — curved and sometimes, flattened. The issue of differing root shapes is not to be ignored, as it may influence the magnitude and distribution of stress in roots.

Many finite element analyses were performed with linear elastic models[6,16], although periodontal ligament has a viscoelastic property. This property exhibits different effects during compression and tension[23], and it was reported that the relationship between occlusal force and distortion of the periodontal ligament was not linear[30]. With a low functional load, the periodontal ligament is easy to deform. However, with an excessive functional load, the periodontal ligament is harder to deform[30]. In light of these phenomena, the periodontal ligament is assumed to have nonlinear elasticity. Consequently, differences in stress distribution within the tooth root will arise between linear and non-linear finite element analyses.

It should also be mentioned that the arrangement of periodontal ligament fibers differs depending on the part of periodontal ligament. Logically then, the mechanical properties of periodontal ligament may vary depending on the arrangement of fibers. Therefore, improvement of the mechanical properties of periodontal ligament should be a subject to be explored and investigated in future studies.

On post and core systems, recent trend indicates that glass fiber posts — besides prefabricated metal posts — have become popular. Although a prefabricated metal post has higher fracture strength than a glass fiber post, stress tends to be concentrated at the tip of post like the cast post and core, leading to fatal vertical root fracture. As for glass fiber post with composite resin core, its Young's modulus is close to those of dentin and the composite resin. As a result, stress is not concentrated at the tip of the post nor at the apex of the root[31]. Therefore, in this research, glass fiber post with composite resin core were selected as the post and core materials instead of a composite resin core with prefabricated metal post or cast post and core.

On the crowns of endodontically treated teeth, Assif and Gorfil[32] reported that with metal crowns, the forces are concentrated in the marginal area, exerting much pressure on the coronal one-third of the root. Within the limitations of this study, it was found that crown materials had little influence on the different magnitudes of von Mises stress in root dentin during function. Further, through this analysis, it was found that among MC, HCC, and ACC, HCC produced the lowest stress concentration in the cervical area. This was chiefly because the Young's modulus of HCC was closer to those of glass fiber post, dentin, and the composite resin core, as compared to ACC and MC groups. Assif and Gorfil[32] also reported that in the transitional area between a rigid and a less rigid material, high stress concentration occurs with increased forces, especially lateral forces. If materials with high Young's modulus like metal or ceramics are used for crowns, stress may be concentrated in the cervical area, as compared with a polymer-based restorative material, thus leading to root fracture.

When HCC was used as the definitive restoration material, it seemed that distortion was not localized, but that it occurred throughout the whole tooth as if the restored tooth were made with a homogeneous material. Hence, owing to the distortion of the whole tooth restored with HCC crown, stress concentration at the cervical area was reduced. It should also be mentioned that von Mises stress at the cervical area was higher for all crown materials in this study treated with MMA and CC than for natural tooth. As for the effect of luting agent, von Mises stress decreased by 37.8 % for MC, 27.1 % for HCC, and 37.0 % for ACC when the luting agent was changed from MMA to CC.

In the oral cavity, teeth are subjected to repetitive *in vivo* loading. Consequently, microleakage will occur within the luting agent. In other words, the type of luting agent used will greatly influence stress concentration in the cervical area. This means that excessive stress concentration in the cervical area can be avoided by using luting agents with Young's modulus similar to those of dentin and the composite resin. In the present study, HCC with CC showed only a slightly higher von Mises stress value than the natural tooth (NT). This implied that it might be possible to approximate its stress concentration to that of NT in the future, when compared to the other definitive restoration materials used in this study. The Young's modulus of CC was 18000 MPa[28] — a value close to those of crown materials, dentin, and the composite resin[7,8,21,26-29]. In sharp contrast, the Young's modulus of MMA was 4500 MPa[29] — a value extremely small compared to those of the crown materials, dentin, and the composite resin[7,8,21,26-29]. Therefore, results of this study revealed that differences in the Young's modulus of resin cements might affect von Mises stress in the cervical area.

No intermediate layer exists between enamel and dentin in natural teeth. However, in clinical restorations, crowns must be cemented with a luting agent. This then gives rise to differences in stress distribution between NT and endodontically treated teeth. Against this background, it is necessary to choose crown materials and luting agents that best resemble the stress distribution in NT.

The fracture strength of a composite resin core with glass fiber post is lower than that of cast post and core[33]. While vertical root fracture is averted with glass fiber post and composite resin core, this kind of post and core system runs the risk of horizontal root fracture. Clinically, however, horizontal root fracture is preferred over vertical root fracture because the former is re-treatable[4]. The Young's modulus of HCC is very close to that of dentin, and similarly the Young's modulus of CC is closer to that of dentin than MMA. Therefore, it was suggested that the combination of HCC and CC could prevent stress concentration in the cervical area. In other words, this combination — *versus* the other materials tested in this study — offered the least possibility of horizontal root fracture.

It helps to put into perspective that regardless of fracture mode, tooth fracture should be avoided as much as possible. Therefore, a definitive restoration should be designed with a view to preventing stress concentration. On this note, the HCC material has undergone improvements in terms of abrasion resistance and fracture strength — by improving the combination of resin matrix and filler or the filler itself[34,35]. Indeed, results in this study showed that HCC was the most suitable material for definitive restorations with respect to root fracture resistance.

CONCLUSIONS

Within the limitations of this study, the following conclusions were drawn:

1. Among MC, HCC, and ACC, HCC gave rise to the lowest stress concentration in the cervical area.
2. When the luting agent was changed from MMA to CC, stress concentration in the cervical area decreased.
3. This study suggested that the cement with a Young's modulus similar to those of dentin and the composite resin produced lower stress levels in the cervical area. Consequently, this reduced the possibility of horizontal root fracture, as compared with the cement with a Young's modulus pronouncedly lower than dentin and the composite resin.

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