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Original Article

Basic Finite Element Analysis of Para-periodontal Ligament in All-ceramic Zirconia Fixed Partial Denture

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Abstract

The purpose of the present study was to investigate the validity of incorporating a para-periodontal ligament in the test mold used in a basic fracture test of a zirconia all-ceramic fixed partial denture (FPD). A simplified three-dimensional finite element analysis model was designed based on the three-unit FPD fracture test. Two types of model, one with and one without a para-periodontal ligament between the abutment and base mold, were fabricated. Microfocus CT of the missing first molar area in a dry human mandible was performed. A three-dimensional model was then fabricated based on the data obtained. A load of 600 N was applied to the center of the pontic and stress distribution observed. The model with the para-periodontal ligament showed stress dispersion to the dental root with rotation of the abutment mold. Stress distribution in the finite element analysis model with a para-periodontal ligament showed greater similarity with that in the mandibular model than with that in the other two models without a para-periodontal ligament.

Key words: All-ceramic zirconia FPDs — Para-periodontal ligament — Finite element analysis — Stress distribution

Introduction

Recent years have seen an increase in the clinical application of all-ceramic prostheses due to the advantages they offer in terms of esthetics and biocompatibility. A number of all-ceramic materials have been developed. One of these, partially stabilized zirconia, has received much attention due to its high fracture load and easy operability, and many studies have investigated its dental application[13].

Most studies on partially stabilized zirconia have employed fracture testing and finite element analysis. With the fracture test, in particular, however, it is difficult to accurately replicate the oral environment, and standardized stainless steel abutment models have had to be developed as a substitute. These are now considered the best alternative from the standpoint of ethics, uniformity, and amount

of material required. Such tests use one of two models: one with[2,3,7,8,12,17] and one without[20] a para-periodontal ligament between the base and abutment mold. In the present study, an elastic rubber material was used to simulate the para-periodontal ligament.

Although many studies have investigated the para-periodontal ligament, few have examined stress distribution in the connecting sections of fixed partial dentures (FPDs), and, to the best of our knowledge, none has compared the results with those of a three-dimensional finite element analysis model based on the same conditions in the human mandible. Although partially stabilized zirconia has a high fracture load, its ductility is low compared with other dental alloys. However, no finite element analysis method is available for evaluating the utility of the para-periodontal ligament based on fracture tests of partially stabilized all-ceramic zirconia FPDs.

The development of the microfocus CT allows the fabrication of a three-dimensional mandibular model that can reproduce details such as cancellous bone, and facilitate detailed observation of stress distribution[11,23]. A human mandibular finite element analysis model reproducing cancellous bone would allow distribution of occlusal force to be observed in detail. The aim of the present study was to compare the results of a standardized abutment model and fabricated model based on the human mandible under the same conditions.

Furthermore, the standardized abutments for the finite element analysis were fabricated based on the results of fracture tests in three-unit all-ceramic zirconia FPDs with different shapes of test mold. The effect of differences in the test molds on stress distribution in the connecting sections of the FPDs was investigated and compared with data obtained using a three-dimensional finite element model fabricated from a human mandible.

Materials and Methods

1. Basic fracture test model fabrication

Figure 1 shows the design of one of the finite element analysis models used. The fabrication of the study model and finite element analysis were performed using finite element analysis software (TRI 3D FEM, Ratoc, Tokyo, Japan). The cylindrical abutment mold was 7.0 mm in diameter and 19.0 mm in height. The top 5.0 mm was made of zirconia and the rest of stainless steel. The two materials were in continuous contact. The two abutment molds, which were 11.0 mm apart, were connected by a pontic with an occlusal surface area of 7.0×7.0 mm and height of 5.0 mm. The circular connecting section was 3.4 mm in diameter, and was located at the center of the lateral surface of the pontic. The minimum distance in the connecting section was 2.0 mm. In the model incorporating a para-periodontal ligament, a 1.0-mm thick elastic rubber was placed around the abutment mold. The contact area with the mold comprised an intermittent contact point (Type 1). Other models included an intermittent contact model without a para-periodontal ligament, in which the cylindrical area surrounding the abutment mold was 7.0 mm in diameter and 19.0 mm in height (Type 2), and one with an abutment and base mold (Type 3). All lateral surfaces and the bottom surface of the base mold were regarded as constraint surfaces. Abutment and base molds were made of stainless steel; the FPDs were made of partially stabilized zirconia; and the para-periodontal ligament was made of rubber; each material constant was used (Table 1). A vertical load of 600 N was applied to the center of the pontic. Principal stress analysis was performed for evaluation. The observation area included the lateral section of the model center.

2. Fabrication of human mandibular model

First, microfocus CT (HMX 225-ACTIS + 4, TESCO Co., Yokohama, Japan) with a minimum slice thickness of 50 μm was used to scan a three-unit FPD removed from the missing first molar area of a human mandible belonging to the Department of Anatomy of Tokyo Dental College. A solid construction image of the mandible was then fabricated based on
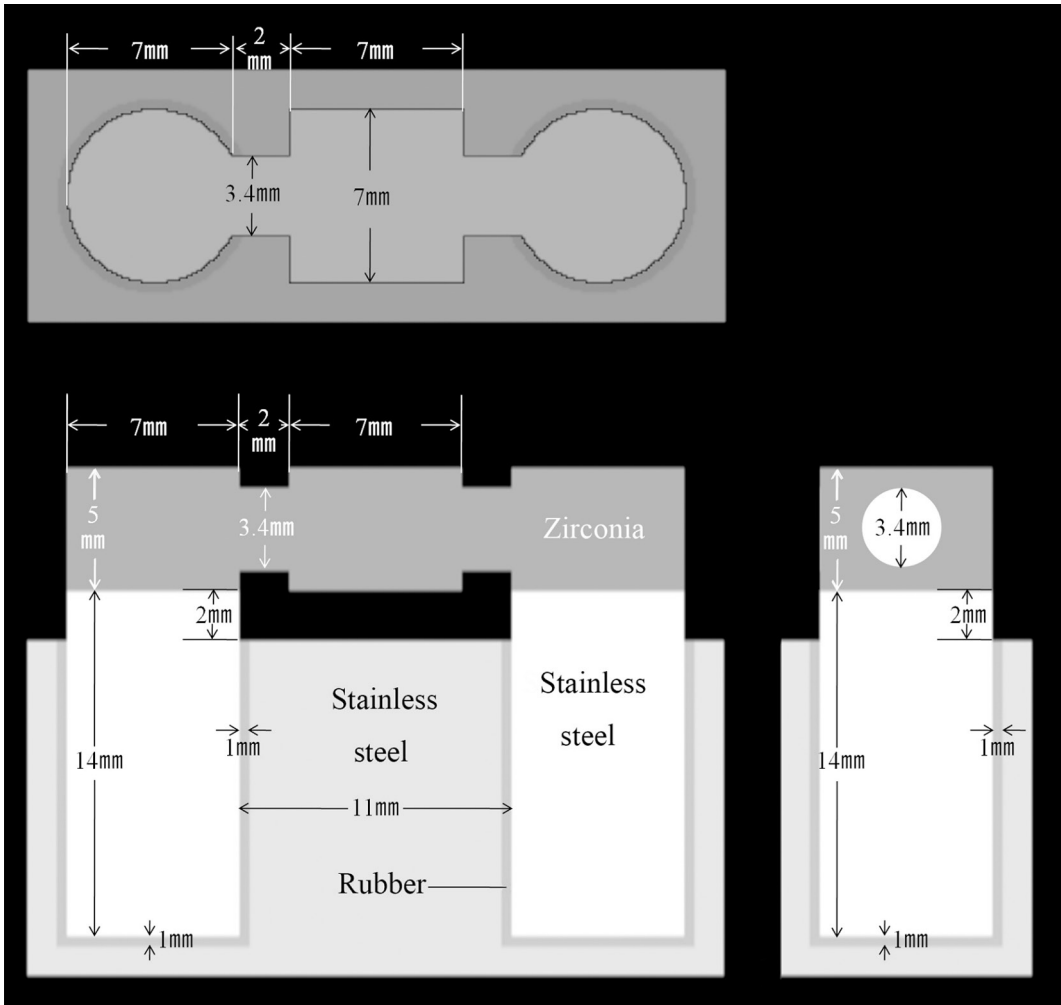
Fig. 1   Experimental design

One of the designs used (Type 1). An intermittent contact model (Type 2), and abutment and base mold models (Type 3) were also used.

the data obtained using three-dimensional construction software and a volume-rendering method (TRI 3D BON, Ratoc, Tokyo, Japan). Arbitrary sections can be set in such images. The internal structure of the area of interest in the cancellous bone was observed. A finite element analysis model was subsequently fabricated using finite element analysis software (TRI 3D FEM, Ratoc, Tokyo, Japan). The three-unit zirconia FPD model with abutments for the remaining second premolar and second molar was superimposed on this model. The distance between the abutments was 25 mm. A cylindrical FPD retainer of 5 mm in diameter was attached to the second premolar and one of 7 mm in diameter to the second molar. An FPD retainer with a simplified diameter was superimposed. The circular FPD-connecting area, which was a 3.4-mm diameter, was positioned in the center of the lateral surface of the pontic.

A pontic with a shape similar to the model used in the basic fracture test was used to connect the FPD abutments and stress distribution

Table 1   Elastic properties of materials modeled

Material	Modulus of elasticity (GPa)	Poisson's ratio
Zirconia	70.0	0.23
Stainless steel	20.3	0.29
Rubber	1.5×10^{-4}	0.46
Bone	13.4	0.3
Tooth	41.4	0.3
Periodontal ligament	2.0×10^{-4}	0.48

evaluated by principle stress analysis under the same loading conditions. A 0.3-mm para-periodontal ligament was present between the abutment root and the mandible. A material constant of partially stabilized zirconia was introduced for the teeth, bone, periodontal ligament, and FPDs (Table 1).

Results

1. Stress distribution in basic fracture test model

Figure 2 shows the finite element analysis results for the lateral sections of each model. Compressive stress is shown as positive and tensile stress as negative. The number of nodes in Types 1 and 2 was 2,439,781, and the one of Type 3 was 2,330,740.

1) Type 1

In both the pontic and connecting area, compressive stress was distributed in the upper area and tensile stress in the lower area. In the abutment mold, compressive stress was observed inside the cervical area, spreading to the bottom. No stress distribution was observed on the lateral side of the abutment mold. Mild compressive stress was distributed in the abutment mold base.

2) Type 2

In the pontic, compressive stress was distributed in the upper area and tensile stress in the lower area. In the upper connecting area, compressive stress was distributed on the pontic side and tensile stress on the abutment mold side. In the lower connecting area, tensile stress was distributed on the pontic side and compression stress on the abutment mold side. In the abutment mold, compressive stress was distributed inside the cervical area and tensile stress outside the bottom of the abutment mold. No stress was distributed on the lateral side of the abutment mold. Mild compressive stress was distributed on the outer surface of the abutment mold base.

3) Type 3

In the pontic, compressive stress was distributed in the upper area and tensile stress in the lower area. In the upper connecting area, compressive stress was distributed on the pontic side and tensile stress on the abutment mold side. In the lower connecting area, tensile stress was distributed on the pontic side and compression stress on the abutment mold side. The abutment and base mold were constructed as a single unit. Compressive stress was concentrated inside the cervical area, spreading to the bottom. Low dispersed compressive stress was distributed in the bottom of the abutment mold.

2. Stress distribution in human mandibular model

Figure 3 shows the finite element analysis results for the lateral section of the human mandibular model. Compressive stress is shown as positive and tensile stress as negative. The number of nodes in the present model was 2,565,217, and the element count was 2,421,480. In the pontic, compressive stress was distributed in the upper area and tensile stress in the lower area. In the connecting area, compressive stress was distributed
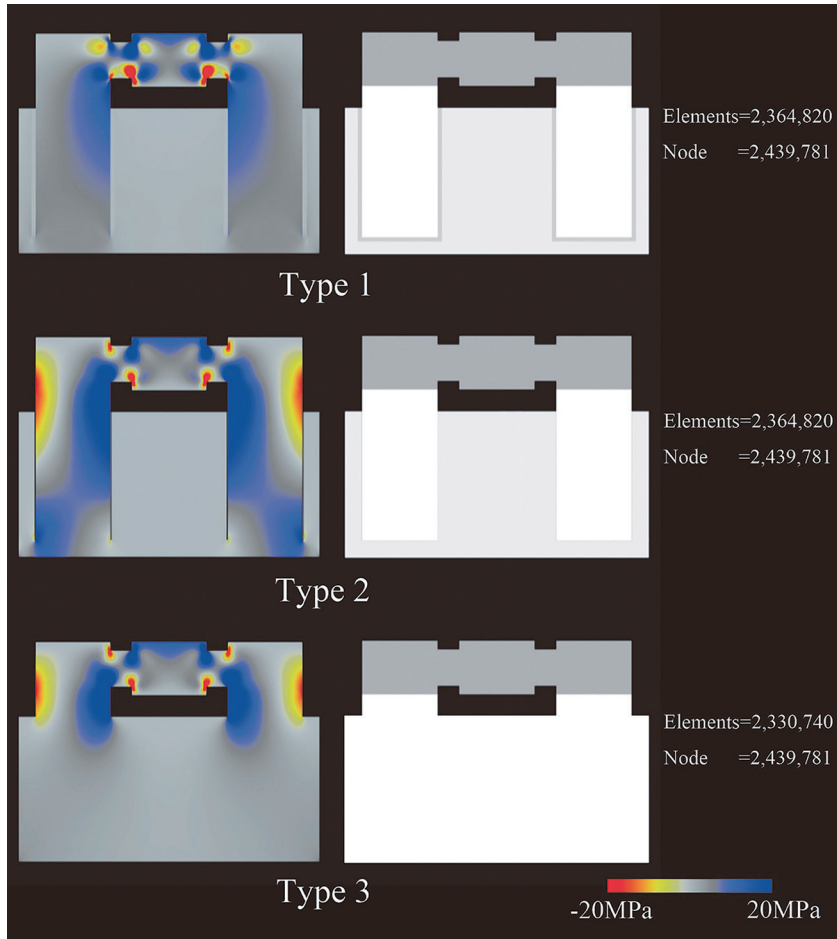
Fig. 2   Stress distribution in each model in basic fracture test
As color bar shows, (+) indicates compressive stress and (−) tensile stress.
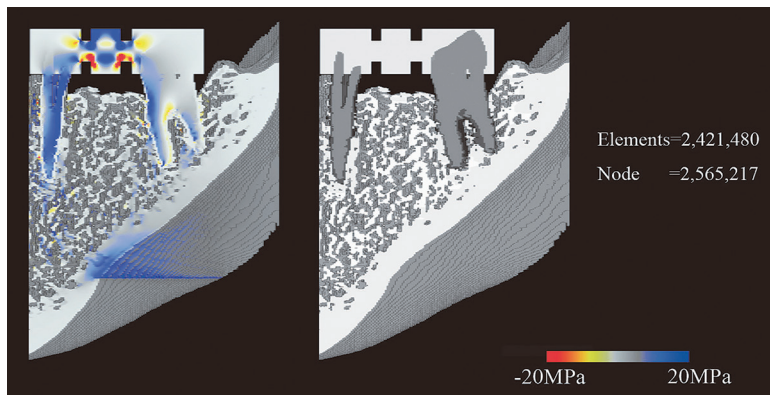

Fig. 3   Stress distribution in human mandibular model
As color bar shows, (+) indicates compressive stress and (−) tensile stress. It is possible
to compare these results with those in Fig. 2 because of standardized conditions.

in the upper area and tensile stress in the lower area. In the abutment root, compressive stress was distributed evenly on the pontic side and tensile stress evenly on the outer surface. Compressive stress was distributed in the alveolar bone between the abutments.

Discussion

It is difficult to accurately replicate the oral environment in the fracture test. In most cases, a standardized abutment model made of stainless steel is used as this offers advantages in terms of amount of material, ethics, and uniformity.

The results of many studies employing finite element analysis have shown good agreement with findings obtained by other parameters. However, there is no value in comparing the results of studies which have applied different material constants and stress distributions. Many studies have investigated the para-periodontal ligament; few, however, have investigated how stress distribution affects the connecting sections of FPDs and, to the best of our knowledge, none has compared the results with those of a three-dimensional finite element analysis model based on the same conditions in the human mandible. The present report, on the other hand, provides an accurate comparison assuming an actual fracture test and a finite element analysis model of the human mandible under the same conditions.

Occlusal force is evenly distributed to the dental roots. Nomoto *et al.* reported that mesiodistal rotation force arises in the abutment root when occlusal force is applied on a pontic due to the physiological mobility of the teeth[9]. The dental root evenly distributes the stress concentrated in the cervical area to the root apex[22]. In the present study, Type 1 showed this kind of stress distribution. Similarities were observed in the finite element analysis results between Type 1 and the mandibular model, including in those for tensile stress on the occlusal surface of the pontic, that on the base surface of the abutment in

the connecting area, compressive stress at the transitional site of the occlusal surface between the abutment and connecting area, and tensile stress in the outer surface of the abutment. The stress distribution phase in the zirconia FPD coping, in particular, was similar to that observed in Type 1. This suggests that setting a para-periodontal ligament allows simulation of stress distribution close to that found in the human body.

The finite element analysis model of the basic fracture test was not designed for use in a clinical setting, and a simplified model based on the model adopted in the fracture test of a three-unit FPD with one missing tooth was used to enhance versatility. Stress distribution in this model was similar to that in the mandibular model. In Type 2, compressive stress was concentrated inside the cervical area, while tensile stress was concentrated outside the cervical area. Stress was also concentrated at the corner of the outer surface of the cylindrical column, which constitutes the bottom surface in an abutment mold. This may have been because there was no continuity between the abutment and the base mold, so compressive stress was distributed to the outer surface of the root bottom due to occlusal force in the direction of rotation of the abutment mold. In Type 3, compressive stress was observed inside a transitional site between the cylindrical column and base (cervical area), while tensile stress was observed outside the transitional site. No stress was observed concentrating at the bottom surface of the abutment mold. The results showed that stress arising from rotational force in the dental root and periodontal ligament was not registered in the one-piece test.

An elastic rubber material is used to simulate the para-periodontal ligament in fracture testing in FPDs. The width of the simulated para-periodontal ligament is usually set at between 0.4 and 1.0 mm[2,3,7,8,12,17,21]. However, this is wider than the actual periodontal ligament. Also, the physical properties of elastic rubber and an actual periodontal ligament may not always the same. Most abutment molds in such studies are cylindrical, and

there is no reproducibility of root shape. Therefore, the present study can only be considered to have reproduced rotation of the abutment mold against a load. It is difficult to directly correlate a fracture load value from the fracture test with actual occlusal force. However, the present fracture test in FPDs showed that stress distribution in Type 1 was more similar to that in the human mandibular model than in the other models, suggesting that the para-periodontal ligament contributed to reproducing stress distribution in the mandibular model.

The Type 3 model assumed a fracture test in a single mold. Zirconia has a higher density than conventional materials used for FPDs. This suggests that if the results of testing using a simplified mold and human mandibular model were similar such studies could be simplified, but the results were different.

In the human mandibular model, the periodontal ligament allowed an even connection between the abutment root and mandibular alveolar area. A width of 0.3-mm was necessary for the periodontal ligament in the human mandible used in the present study. An FPD-connecting area should be circular with a 3.4-mm diameter based on the 9.0-mm^2 sectional area recommended for partially stabilized zirconia three-unit FPDs[1,14–16]. Although a space equivalent to a core was confirmed in the second premolar, no interpolation was performed as continuity was maintained in the retainer and all circumferences, and adding settings in core areas such as resin might have skewed the results. We believe that there was no influence on stress distribution in the zirconia. Marked stress distribution was observed in the lower part of the connecting area, which agrees with an earlier report regarding the initial fracture point of a zirconia FPD[4,10]. Other studies using a para-periodontal ligament showed a decrease in fracture load compared with a fracture test in a one-piece mold[2,3,7], suggesting that para-periodontal ligaments should be applied in clinical studies. In the present study, compressive stress was observed in the upper area and tensile stress in the lower area of the connect-

ing section in Type 1. In Types 2 and 3, compressive stress was distributed in the upper area of the connecting pontic and tensile stress in the upper area of the abutment. In Types 2 and 3, stress in the connecting area was compensated for, resulting in a decrease in stress distribution. The present results suggest that the fracture load value was higher in Types 2 and 3 than in Type 1 in the fracture test in the connecting area. A correlation was observed between the results of the finite element analysis and those of the fracture test.

Tooth shape was not taken into consideration in the abutment, and the abutment and abutment mold were constructed as a single piece with continuous contact. The stainless-steel abutment mold and abutment were believed to be tightly attached. No material such as cement was added to simplify the study. The present results support those of earlier studies showing that fracture is often confined to the connecting area[5,6,8,18,19].

The present results suggest the advantage of reproducing the para-periodontal ligament when investigating stress distribution in the mandible over using a one-piece test mold.

Conclusion

The following conclusions were drawn based on a finite element analysis.

In the model with the para-periodontal ligament, compressive stress was dispersed throughout the root area in response to rotational force from an abutment caused by a load applied in the pontic. Stress distribution in the finite element analysis model with a para-periodontal ligament was more similar to that in the mandibular model than to that in the other two models without a para-periodontal ligament.

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