Influence of one-wall remaining coronal tooth with resin abutment and fiber post on static and dynamic fracture resistance

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The objective of this study was to determine the influence of height and thickness of the one wall remaining coronal tooth structure on the fracture resistance of an endodontically treated root with resin abutment build-up using resin composite and fiber-reinforced resin composite post. Static and dynamic fracture tests were performed by placing the remaining tooth wall on the tensile side and applying loads at an angle of 30° from the tooth axis. Superior static fracture resistance was observed when the wall remaining on the tooth had a height and thickness greater than 1.0 mm. The dynamic fatigue test showed high loading capacity or fracture resistance in specimens with large height and thickness. The dynamic fatigue test showed the influence of the remaining tooth structure on fracture resistance clearly. In conclusion, the static and dynamic fracture resistances increased with the height and thickness of the one wall remaining tooth structure.

Keywords: Fracture strength, Dynamic fatigue, Endodontically treated tooth, Fiber post, Remaining coronal tooth

INTRODUCTION

An endodontically treated root, where a large portion of the structure is lost due to decay, requires abutment (post and core) build-up. Conventional prefabricated or cast metal posts used for abutment build-up have disadvantages such as allergic reactions and biological side effects by metal ion elution due to microleakage and corrosion, crown displacement due to lack of retention between dentin and metal, and root fracture due to the difference in elastic modulus of metal and dentin14. Abutments made with resin, and fiber-reinforced resin composite posts (FRC posts) have a smaller elastic modulus than conventional metal posts. The smaller elastic modulus can prevent longitudinal root fracture on the root canal treated tooth improving its chances for long-term survival12. In addition, this fabrication method is also advantageous from the viewpoint of esthetics in that the color of the restoration harmonizes with the rest of the dentition.

After abutment build-up, it is necessary to place a crown and adequately maintain the final prosthesis. Retention of the restoration is dependent on the bond strength of post and root canal dentin15, abutment form, and the presence or absence of a ferrule on the remaining tooth7-11. In particular, a ferrule on the remaining coronal dentin of the tooth contributes to the increase of fracture resistance of the resin abutment improving the 3-year survival rate16. For FRC posts, a ferrule height and thickness greater than 2.0 mm and 1.0 mm, respectively, are required12. For metal posts, a ferrule height and thickness of 1.5 to 2.0 mm and 0.5 mm, respectively, are effective for maintaining crown restoration. In clinical dentistry, securing an adequate height of 2.0 mm and thickness of 1.0 mm on the remaining coronal tooth can be difficult in certain conditions13. These conditions include low crown height, significant carious lesion in the proximal region causing damage to the supragingival tooth, and mesial-distally flattened anatomical form of the maxillary premolars.

FRC posts could withstand large loads when applied in the direction perpendicular to the direction of the glass fibers and could significantly bend when loads were applied horizontally; however, resin abutments were weak against horizontal loads14. The bond strength of resin abutment to root canal dentin was also suggested to contribute to post retention15,16. When considering the retention of the final prosthesis on the root canal treated tooth built-up with resin, it is necessary to consider loads from the horizontal and vertical directions. Nishimura et al. performed a cyclic fatigue test assuming occlusion in the anterior region and reported that the anterior teeth could tolerate a load of 250 N for $3 \times 10^6$ cycles17. In addition, a study investigated the relationship between fracture resistance and residual tooth wall of the anterior maxillary teeth, and they reported that a large fracture resistance was observed when tooth structure remained on the palatal surface (tensile side)18. Molars must satisfy the mechanical requirement to withstand large repetitive loads of occlusion. In the premolar region, resin abutment with FRC post effectively retains restorations even if there is no ferrule on the tooth19. Studies have reported that the heights of the lingual or one of the proximal walls affect fracture resistance10,11,13. However, the load-bearing capacity and durability of abutments reinforced with resin composite and FRC post when there is very little coronal tooth remaining, has not been clarified.
The objective of this study was to determine the influence of height and thickness of the one wall remaining coronal tooth structure on the fracture resistance of endodontically treated root with resin abutment build-up using resin composite and FRC post. The null hypothesis was as follows: the height and thickness of the ferrule on the remaining coronal tooth do not affect either the static fracture resistance or the dynamic fracture resistance of the resin abutment structure after cyclic loading.

MATERIALS AND METHODS

Root preparation
A total of 46 bovine anterior teeth, which were stored frozen, were used for this study. The soft tissue surrounding each root was removed using a hand scaler, and the pulp was extracted using an endodontic file. The crown of the individual tooth was cut 2 mm above the cement enamel junction (CEJ). Specimens with root canal diameters of less than 3 mm on the coronal surface were used. Although the difference in the morphology was not considered thoroughly, specimens with similar root canal morphology were sectioned and selected. As shown in Fig. 1(a), each root was placed in an acrylic ring (diameter 19 mm, height 20 mm) with auto cured acrylic resin (Tray Resin, Shofu, Kyoto, Japan) up to 3 mm below the CEJ. The root canal was irrigated with 3% sodium hypochlorite (NaOCl; ChlorCid® J, Ultradent Japan, Tokyo, Japan) and 18% ethylenediaminetetraacetic acid (EDTA; Ultradent® EDTA 18%, Ultradent Japan) for 30 s, then washed with water and air-dried. The root canal was obturated with gutta-percha (Gutta-percha obturator, Morita, Tokyo, Japan). Tooth preparation was performed on the remaining tooth using a diamond bur (101 LRD, Shofu); the margin was established at the CEJ with deep chamfer preparation. Thereafter, a 3.0-mm drill was used to prepare the root canal with a diameter and depth of 3 mm and 8 mm, respectively. Coronal tooth structure 2 mm above the CEJ was removed, then three of the four walls were removed, leaving the palatal wall as the ferrule. The height and thickness of the ferrule varied depending on the group (Fig. 1(b)). Table 1 shows the combination of the height (H) and the thickness (T) of the one-wall remaining on the coronal tooth.

Resin abutment build-up
Before abutment build-up, 40% phosphoric acid (Ketchant GEL, Kuraray Noritake Dental, Tokyo, Japan) was applied to each FRC post (1.6 mm in diameter, Fiber post, GC, Tokyo, Japan); these were washed with water, dried, then silane coupling agent (CERAMIC PRIMER II, GC) was applied. A bonding agent (Clearfil® Universal Bond, Kuraray Noritake Dental) was applied to the root canal walls, aired for 10 s with mild air, and then irradiated for 10 s with an LED irradiator. An abutment was built up via direct method using the FRC post and resin (Clearfil® DC Core Automix® ONE, Kuraray Noritake Dental). The height of the build-up was 3 mm from the margin. Each specimen was light irradiated for 40 s from 5 directions. The abutment tooth was prepared at an axial inclination of 6° with deep chamfer preparation using a surveyor and diamond bur (101 LRD, Shofu).

Crown fabrication and placement
A conventional casting method was used to fabricate a crown for each specimen. An impression was made with vinyl polyester silicone rubber impression material (Fusion II, GC), and a working model was constructed using type 4 dental stone (New Fuji rock, GC). The crown was designed to have a height of 5 mm from the margin assuming the maxillary premolars, and the crown shape was simplified to 2 cusp heads. A crown wax pattern was made on the working model. A 2-mm hemi-spherical hole was prepared below the cusp tip on the inner slope of the palatal surface of the wax pattern for the indentation of load point, as shown in Fig. 2(b). The wax pattern was invested in cristobalite investment material (Ideavest, GC) and casted with silver-palladium-copper alloy (Ishifuku G12, ISHIFUKU, Tokyo, Japan). After adjusting and polishing the cast, the inner crown surface was sandblasted. Primer (Metal Primer II, GC) was applied then bonded to the abutment using adhesive resin cement (ResiCem, Shofu). A load of 49 N was applied for 5 min. Light irradiation was performed for

| Code   | H0T0 | H5T5 | H10T5 | H10T10 | H20T10 |
|--------|------|------|-------|--------|--------|
| Height (mm) | 0    | 0.5  | 1.0   | 1.0    | 2.0    |
| Thickness (mm) | 0    | 0.5  | 0.5   | 1.0    | 1.0    |
Specimens constructed with resin abutment and crown restoration in resin mold was fixed at an angle of 30° from the vertical axis, and load was repeatedly applied vertically with indentation jig (a). Fracture point was established as the point which shifted more than 1.0 mm during loading, and then the fracture line could be seen in (b).  

1 to 2 s initially to remove excess cement. Then, light irradiation was performed for 20 s from 4 directions. The specimen was kept in a container filled with water and left in an incubator at 37°C during 24-h storage after specimen preparation.

Static loading test
A static fracture test (n=5) was conducted on specimens while placing the ferrule on the tensile side. A universal testing machine (Autograph AG-I 20kN, Shimadzu, Kyoto, Japan) was used to apply a load at a 30° from the root axis at a crosshead speed of 1.0 mm/min until the load was reduced by 25% or more from the maximum load. The static fracture resistance value was expressed as the average the maximum load and standard deviation. After testing, the fracture mode of the abutment tooth was determined using a digital microscope (VH-5000, Keyence, Osaka, Japan).

Cyclic loading test
Cyclic load fatigue test for dynamic loading test was conducted with three groups: H0T0, H10T5, and H20T10. Each specimen shown in Fig. 1 was placed on the cyclic load fatigue servo-hydraulic universal testing machine (EHF-FD 05, Shimadzu) so that load was applied at an angle of 30° from the vertical axis. The apparatus with specimen before and after loading is shown in Fig. 2. The indentation on the crown restoration was loaded using a 2 mm hemisphere cusp made of stainless steel. A warm-up load of 5×10^5 cycles was performed at the load ranged from 10 to 200 N and 10 Hz using sin-wave stress method as a preconditioning measure. Then a load of 3×10^5 cycles was applied at the load ranged from 10 to 400 N and 10 Hz using sin-wave stress method, and cyclic maximum loads were applied in increments of 500, 600, 700, and 800 N. Testing was undertaken until the specimen fractured; the fracture point was established as the point which shifted more than 1.0 mm during loading. The fracture mode below the cervical region of the crown and above the embedding resin was determined using a digital microscope (VH-5000, Keyence). In addition, fracture progression was observed above or below the end of the embedded resin. Seven specimens in each group were prepared.

Micro-CT observation
Selected specimens were studied under the microfocus X-ray real-time radiography/computer tomography system (micro-CT; HMX 225-ACTIS+4, TESCO, Kanagawa, Japan) to determine the fracture mode inside the root, and 3D Trabecular Bone Structure Analysis 1 (TRI/3D-BON, RATOC System Engineering, Tokyo, Japan) was used to perform 3-dimensional (3D) reconstruction.

Statistical analysis
The static fracture resistance values obtained were subjected to one-way analysis of variance analysis (ANOVA) and multiple comparison test by Tukey-Kramer method. The cyclic load fatigue test values for each combination were subjected to Wilcoxon’s significant difference test using the Kaplan-Meier method. The significance level was set at 5% (α=0.05).

RESULTS
Static fracture resistance
Figure 3 shows the static fracture load values of resin abutment tooth with varying height and thickness on the remaining wall. The fracture load of the sample with no remaining wall (H0T0) was the smallest at 907±62 N. The fracture load of H10T10 and H20T10 showed larger values at 1,208±227 N and 1,147±253 N, respectively. As a result of statistical analysis, a significant difference was observed between H10T10 and H0T0, between H10T10 and H5T5, and between H20T10 and H0H0. As shown in Fig. 4, the fracture mode of the static fracture test was divided into three groups: core fracture, root fracture less than 3 mm, and root fracture greater than 3 mm. In H0T0 and H5T5, core fracture occurred in 40% (two out of five) or 60% (three out of five) of cases and root fracture greater than 3 mm in 20% (one out of five) of cases. For H10T10 and H20T10, root fracture greater than 3 mm was seen in 40% (two out of five) or 60% (three out of five) of cases. As the height and thickness of the remaining coronal tooth increased, incidences of root fracture greater than 3 mm tended to increase.

Survival rate for cyclic load fatigue test
Figure 5 shows the cyclic load fatigue value and the survival rate of specimens. Cyclic load fatigue value decreased significantly compared to the static fracture load value. The survival rates of H0T0 and H10T5 under a load of 400 N were 14% (one out of seven) and 71% (five out of seven), respectively. All samples fractured during a load value of 500 N for H0T0 and 600 N for H10T10. In H20T10, the fracture was observed for the first time under a load of 600 N. Still, the survival rate after the cyclic loading test was 29% (two out of seven) at 700 N. As a result of statistical analysis, significant differences were observed among the three groups.
Fig. 3  Static fracture load of resin abutments with one-wall remaining coronal teeth.
* indicated significant difference, \( p < 0.05 \) (ANOVA and Tukey-Kramer test)

Fig. 4  Classification of fracture mode after static fracture test.
The fracture mode was classified to: only core fracture, less than 3 mm root fracture, and more than 3 mm root fracture.

Fig. 5  Survival rate of different coronal teeth structure after cyclic loading test.
The load was increment after loading at \( 5 \times 10^3 \) cycles.

Fig. 6  Classification of fracture mode after cyclic fatigue test.
The fracture mode was classified to: only core fracture, root fracture without one-wall fracture, and root fracture with one-wall fracture. The arrow indicates the initial fracture line.

Fig. 7  Micro-CT image of H0T0 specimen (2 mm below the CEJ) fractured at less than 3 mm (a) and H20T10 specimen (5 mm below the CEJ) fractured at more than 3 mm (b).
The arrows indicate the fracture line of root and core. Root fracture in (b) was happened to failure of the build-up resin composite.

Observation of failure mode revealed that the core fracture occurred in 43% (three out of seven) of cases in H0T0. For H10T5 and H20T10, all specimens displayed root fractures greater than 3 mm (Fig. 6). In H10T5, 71% (five out of seven) of the samples showed root fracture without cervical fracture, but in H20T10, all samples showed root fracture with cervical fracture.

When H0T0 specimen with root fracture less than 3 mm was observed with the micro-CT, fracture was observed from the abutment resin on the tensile side to where the load was applied on the crown and root dentin (Fig. 7(a)). In a specimen of H20T10 where fracture was greater than 3 mm, fracture was observed on the tensile side from the ferrule into the resin abutment (Fig. 7(b)). In other words, in specimens with large fracture...
DISCUSSION

Test method
In this study, an FRC post and resin composite were used to build up the resin abutment on the root of the bovine tooth, and a maxillary premolar crown was fabricated and bonded on each specimen. The anatomy and composition of bovine dentin are similar to human dentin; therefore, it is often used for in vitro tests\textsuperscript{20}. Static and dynamic fracture tests were carried out on teeth abutment reinforced with resin composite through static and cyclic load fatigue tests. During the static fracture load test, loads were applied to specimens at an angle of 30° until fracture. This static fracture test involved a load from one direction and evaluated fracture resistance during a single occlusion, which does not simulate the oral environment.

Meanwhile, the chewing cycle in the oral cavity is repeated with a variety of small occlusal forces. The mandibular jaw comes in contact with the maxillary jaw in the anterior region at an angle of approximately 45°\textsuperscript{21}. The occlusal force in the anterior region is approximately 200 N. In contrast, occlusal force in the molar region can be as large as 300 to 600 N. In this study, contact between the maxillary molar cusps was assumed. The study was designed in reference to the implant durability test (ISO 14801)\textsuperscript{22} where an indenter in the shape of a half-cylinder (hemisphere cusp, 1.0 mm radius) was used to apply the loads. Evaluations were made using a stepped-load protocol where loads were increased incrementally to determine specimen durability. This stepped-load protocol is an intermediate between the conventional load-to-failure protocol and the time-consuming low-load fatigue test\textsuperscript{23}. In addition to being able to consider the influence of the occlusal forces on the abutment structure, this stepped-load cyclic fatigue test can simulate the durability (fracture resistance) of a restoration better by accelerating the lifecycle of the restoration compared to the static fracture test.

Fracture resistance of root with resin abutment
As a result of the static fracture test, H10T10 and H20T10 displayed larger fracture loads than H0T0 and H5T5. Therefore, the first null hypothesis that the height and thickness of the one wall remaining on the tooth does not affect on the static fracture resistance of the resin abutment was rejected. Furthermore, the cyclic load fatigue test with increased incremental loading was observed significant differences between H0T0, H10T5, and H20T10; the greater the height and thickness of the remaining coronal tooth wall, the greater the durability of the resin abutment. Therefore, the second null hypothesis that the height and thickness of the one wall remaining on the tooth do not affect the fracture resistance of the resin abutment after cyclic loading was also rejected.

Many studies have reported that the retention of crown prosthetic restorations increases with a ferrule on the remaining tooth when the abutment tooth is built up with resin and FRC posts\textsuperscript{4,12,23-25}. For adequate retention of the restoration, the remaining coronal tooth has a height greater than 1.5 mm\textsuperscript{12}, and when the remaining coronal tooth does not have at least one wall with a height of 2.0 mm\textsuperscript{25}, an FRC post is necessary. A ferrule plays an important role for an endodontically treated root to retain a restoration; however, the presence of a ferrule, even just on one wall, improves overall prognosis\textsuperscript{25}. In addition, it has been reported that adequate bond strength between the remaining tooth and resin abutment improves the retention of restoration even if the ferrule thickness is less than 0.5 mm\textsuperscript{21}.

In this study, large static fracture loads, which were indicated in the specimens with remaining coronal tooth height and thickness of 1.0 mm, support the previous reports that the presence of a ferrule improves retention strength. However, in the static fracture load test, no significant differences were observed between specimens with the same wall height (H10T5 and H10T10) and thickness (H5T5 and H10T5, H10T10 and H20T10). Therefore, further study is required to determine whether height and thickness contribute to static fracture load.

In the cyclic load fatigue test in which the load was incrementally increased, the height and thickness of the remaining wall significantly influenced the fracture load. The static fracture load of the specimen with no remaining wall was approximately 900 N, which was sufficiently larger than the fracture load value required for premolar and molar teeth\textsuperscript{26}. Table 2 shows the mean and standard deviation of loading cycles for the fractured

| Table 2 | Total number of repeated loading (mean and standard deviation) during cyclic fatigue test of tooth abutment built-up with resin composite and FRC post |
|---------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Load at cyclic fatigue test, N                                                                 | 400                  | 500                  | 600                  | 700                  | 800                  |
| H0T0 (NFS*)                                   | 6,558±991 (6/7)      | 36,227 (1/7)         | None                 | None                 | None                 |
| H10T5 (NFS*)                                  | 9,756 (1/7)          | 39,823±5,040 (5/7)   | 74,800 (1/7)         | None                 | None                 |
| H20T10 (NFS*)                                 | All passed           | All passed           | 86,332 (1/7)         | 100,111±4,533 (5/7)  | 134,896 (1/7)        |

*NFS: number of fractured specimen
specimens and the total number of cycles (from a load of 400 N). However, in the cyclic load fatigue test, the resin abutment (H0T0) fractured at 500 N or less in all specimens, that is, they in the cyclic load test were fractured in half load or less at the static fracture load. Furthermore, the average fracture cyclic number of the fractured six specimens, H0T0, loaded at 400 N was $6.6 \pm 1.0 \times 10^4$ cycles as shown in Table 2, and the cycles did not reach one-quarter of the planned load number ($3 \times 10^4$ cycles). Similarly, the fracture load decreased to 40 to 60% of the static fracture load for H10T5 and 30 to 48% for H20T10. The fracture load was lower compared to the static fracture test because micro cracks propagated during repetitive loading. In other words, micro-cracks created during small loading propagated into the resin composite and tooth root during cyclic loading. The resin abutment with one wall involving a coronal tooth could exhibit larger resistance towards the propagation of microcracks. These results indicated that the presence of a single remaining and greater height and thickness of this remaining structure increase the fracture resistance of the resin abutment and retention of the final restorations.

Fractured mode
Since the elastic modulus of FRC post is similar to root dentin, teeth with build-up resin abutments with FRC posts are less likely to result in vertical longitudinal root fracture than with cast metal posts$^{25}$. However, the resin abutment has shown similar clinical performance to the cast metal post$^{26}$. The fracture mode observed in specimens using metal-cast post with luting cement to root canal displayed root fractures where tooth repair was impossible. When FRC post was used with resin abutment, fracture occurred in the resin abutment structure, and tooth restoration could be done$^{29,30}$. On the other hands, there were still reports of root fracture in cases where FRC post and resin were used to reinforce tooth abutment$^{34-36}$. The fracture mode of the resin abutment after the static fracture load test tended to increase the propagation of cracks greater than 3 mm as the height and thickness of the remaining one-wall tooth increased. H20T10 displayed a less severe fracture (under 3 mm fracture) than H10T10, which had the same thickness. Although the fracture forces of both H10T10 and H20T10 showed no significant difference, H20T10 showed 40% (two out of five) core fracture, and H10T10 showed 40% (two out of five) less than 3 mm fracture. Since the fracture mode was visually confirmed using a microscope, the relationship with resin abutment in the root canal was not observed. Therefore, the different fracture mode of H10T10 and H20T10 remains unclarified and will require further investigation in the future. During the cyclic load fatigue test, where the load was incrementally increased, root fracture greater than 3 mm occurred more frequently as the fracture load increased. This was because the load was applied towards the remaining wall on the tensile side, causing the force to concentrate on the remaining tooth. Since the resin abutment structure is integrated with the teeth through adhesive agents, fracture occurred along with the root.

When there is no wall remaining or when the remaining tooth on the wall is small, stress concentrates at the interface between the FRC post and core on the tensile side and between the resin abutment and metal crown during cyclic loading. Stress at the interface caused the fracture to occur because a large shear force was applied to the resin abutment due to the difference in modulus of elasticity between the metal crown and the resin abutment. Therefore, the single wall remaining on the tooth plays an important role during load-bearing, but when there is excessive occlusal force, fracture occurs in the resin abutment and remaining coronal tooth. This is why evaluation of crown retention on teeth reinforced with resin composite and FRC post should be done using static fracture load test and cyclic load fatigue test to reproduce clinically encountered root fracture modes.

Clinical significance
When the mandibular premolar crown height and mesiodistally flattened anatomical form of the maxillary premolars are considered, securing an adequate height of 2.0 mm and thickness of 1.0 mm for the abutment ferrule can be difficult. By applying a ferrule around the entire tooth during abutment build-up, stress concentrates in the cervical region improving crown retention$^{34}$. Even if the tooth is preserved, ferrules lacking thickness do not satisfy the mechanical requirement, and this fragile structure may become a factor for fracture$^{35}$. In this study, clinically encountered abutment failure modes could be reproduced by investigating static fracture resistance and simulating the restorations’ life cycle through repetitive loading. The occlusal force at the molar ranges from 600 N to 900 N, therefore the durability of resin abutment requires a force greater than 600 N. Clinically necessary fracture resistance of more than 600 N can be ensured by leaving one wall on the tensile side of the restorations. However, when a repetitive load was applied on the remaining wall, crack propagation greater than 3 mm occurs from the CEJ towards the root, and fracture occurred in the resin abutment along with the remaining tooth. This type of fracture in a clinical setting is called an infrabony fracture, where tooth repair is difficult. Therefore, adequate height and thickness of one wall remaining coronal tooth effectively increases fracture resistance; however, it is important to consider that when fracture of resin abutment occurs, it may be accompanied by a root fracture. For these reasons, when large occlusal force is expected in a clinical setting, the tooth should be left even if it is just one wall, and an FRC post should be used to improve durability.

CONCLUSIONS
In this study, a tooth with one-wall remaining coronal dentin was built up with resin composite, and fracture resistance was evaluated by static fracture test and
cyclic load fatigue test. Consequently, the following points were concluded.

1. Compared to a tooth without any remaining coronal dentin (without ferrule), a large fracture resistance was indicated when the height and thickness of the one-wall remaining coronal tooth were greater than 1.0 mm.

2. Resin abutment without any remaining coronal tooth wall (without ferrule) still displayed static fracture resistance to withstand the force of more than 800 N.

3. The greater the height and thickness of the one-wall remaining coronal tooth, the greater the fracture resistance during cyclic loading. The greater the fracture resistance, the greater the incidence of root fracture.

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CONFLICT OF INTEREST

We have no conflict of interest.

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