Fabrication of a Functionally Graded Dental Composite Resin Post and Core by Laser Lithography and Finite Element Analysis of its Stress Relaxation Effect on Tooth Root

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Laser lithography was applied for Computer Aided Design and Computer Aided Manufacturing (CAD/CAM) fabrication of dental prostheses made of composite resin. First, the conditions to obtain the optimum resolution for photo-curing were determined, and then a composite resin full crown was fabricated by laser lithography. Second, a functionally graded composite resin post and core which had gradient elasticity in the post, was manufactured by the gradual change in the filler contents of the composite resin. Finally, stress analysis of the functionally graded post and core was performed by a two-dimensional finite element method. This demonstrated the effects of reducing the stress concentration around the apex of the post.

Key words: CAD/CAM, Post and core, Stress relaxation

INTRODUCTION

A cast metal post and core treatment has been accepted and used for the restoration of endodontically treated teeth for a long time. It has been strongly argued that the cast metal post and core can reinforce the weak teeth resulted from endodontic treatment¹⁾. In contrast, the incidences of detachment and root fracture after the cast metal post and core treatment have exceeded the expected clinical cases. According to Iwanami *et al.*²⁾, it was shown that more than 90% of the endodontically treated teeth received cast metal post and core treatment in their hospital. In addition, a higher frequency of dental prostheses was observed in Japanese patients compared with those in other countries³⁾. Recently, many mechanical investigations relating to the post and core have been carried out, and stress concentration in the post was identified as one of the causes of the increased incidences of root fracture after the implantation of the cast metal post and core^{4–8)}. Hence, a study concerning a method to reduce the stress concentration in a post has been necessary. Recently, much attention has been paid to the use of composite resin for the fabrication of the post and core, although controversies on this subject exist. In most studies, it has been reported that the post and core made of composite resin causes less root fracture because it had a stronger adhesion to dentin and the elasticity of dentin and composite resin are closer. On the other hand, some studies reported a higher

incidence of root fracture due to stress concentration in the composite resin post with the insertion of a prefabricated metal post^{4,9)}.

Thus, the present study was designed to construct and investigate a countermeasure against root fracture caused by stress concentration at the post. For this purpose, the possible advanced performance of the functionally graded (FG) composite resin post and core was investigated over the existing post and core systems. This post and core was made with the gradually changing elasticity for the post. Thereby, it was expected that the functionally graded post and core could decrease the incidence of root fracture caused by stress concentration around the apex of the post. However, the fabrication of the functionally graded post and core was impossible using conventional methods with manual procedures. Consequently, we focused on laser lithography which can accurately fabricate solid models by laminate modeling.

The laser lithography technology, one of the CAD/CAM systems, fabricates solid models. It depends on the photochemical reaction between a laser beam and light curing resin. It has often been applied in the field of dental surgery. Skeletal models fabricated by laser lithography are used at clinical levels for both the simulation and planning for orthognatic or implant surgery. However, its application in the field of dental prosthesis remains very limited. Only a very few attempts have been made to manufacture dentures¹⁰⁾ and dental arches¹¹⁾. Ueda *et al.*¹²⁾ fabricated cast metal crowns through the lost wax process using resin patterns with the help of laser lithography. In another study, ceramic prostheses were fabricated, starting with porcelain-resin composites made by laser lithography and followed by a resin-burning process¹³⁾. These studies did not fabricate complete prostheses directly, and there were still complicated procedures even after the fabrication process by laser lithography.

The present study used laser lithography for the fabrication of complete prostheses directly from composite resin, then the fabrication of the functionally graded composite resin post and core, and finally evaluation of the mechanical effects of the functional gradience. The modeling performance of ultra-violet (UV) curing composite resin was examined first under the polymerization conditions of the laser lithography apparatus. Then, the fabrication of the functionally graded composite resin post and core was performed under the optimum conditions obtained and stress distribution was analyzed by a finite element method (FEM), so that the effect of stress relaxation by the functionally graded post and core could be investigated.

MATERIALS AND METHODS

1. The laser lithography device

The laser lithography device used in the present study was SOUP400GH (CMET Inc., Tokyo, Japan). The beam was a Helium-Cadmium laser (wavelength: 325 nm) with a spot diameter of 0.2 mm. A galvanometer mirror was used for the laser scanning device. Laser output was in the range of 11-14 mW in this experiment.

2. Modeling procedures by laser lithography

Fig. 1 shows a schematic illustration of the laser lithography device. After geometric model data for fabrication by laser lithography were made using a computer, cross-sectional measurements were obtained by multiple horizontal cross-sectioning of the model at equal intervals. Laser scanning trace data were input into this cross-section data for the polymerization of the UV cured composite resin.

After moving down the stage by one layer thickness (0.1 mm), composite resin paste was pressed with a polyethylene film on it using a glass mixing slab, and positioned at the base level of laser scanning. After the slab was removed, the new stratum was polymerized with laser beam scanning. The next composite resin layer was added onto the previous layer. These procedures were repeated until laser scanning was over. Finally, the manufactured solid models were removed from the stage and cleaned up by steam.

3. Determination of optimum modeling conditions and setting of full crown model (1st experiment)

1) Preparation of UV curing composite resin

Urethane dimethacrylate (di(methacryloxyethyl)trimethyl hexamethylene diurethane)

Fig. 1 Schematic illustration of modeling procedure by laser lithography.

Table 1 Composition of UV curing composite resin.

Materials	Lot No.	Manufactures
Urethane dimethacrylate (UDMA)	50150	Negami ¹
Triethylene glycoldimethacrylate (TEGDMA)	SKH4994	Wako ²
Benzoin methyl ether (BME)	57H3483	SIGMA ³
Silica filler (Crystalite VX-SR)	9E-0803	Tatsumori ⁴
Powdered glass fiber filler (Microglass)	K9390	Nippon Sheet Glass ⁵

¹ Ishikawa, Japan

² Osaka, Japan

³ St. Louis, MO, USA

⁴ Tokyo, Japan

⁵ Osaka, Japan

(UDMA) (50 mol%) with triethylene glycol dimethacrylate (TEGDMA) (50 mol%), was used as the base monomer for the resin matrix. Benzoin methyl ether (BME) (1 wt%) was added as UV polymerization initiator (Table 1).

Quartz particles (Crystalite VX-SR, Tatsumori, Tokyo, Japan) with a mean size of 2.0 μm were used for the filler. They were treated with a silane coupling agent (3-methacryloxypropyl trimethoxysilane) on their surfaces. The filler content of composite resin was set to 70 wt%. After mixing the materials, the paste was degassed using a deaerator.

2) Measurement of polymerized composite resin width by single beam scanning

The cured zone was formed by single UV laser beam scanning on the surface of composite resin paste (Fig. 2(a)). The zone was widened larger than the laser beam spot diameter because of beam scattering. The cured zone had a hog-backed shape as shown in Fig. 2(b). The measurement of the cured width was performed at ten places of the cured zone for the scanning rate conditions of 150, 200, 250, 300 and 350 mm/second, respectively, under a reading scale microscope.

3) Measurement of cured depth

The cured depth was measured for square models of 10×10 mm fabricated by laser beam scanning. Different scanning speeds of 150, 200, 250, 300, 350 mm/sec and different scanning intervals of 0.20, 0.30 and 0.40 mm were applied. Laser scanning on the models was done only for the x-direction. The thickness of the models was considered as the cured depth in this study. The thickness was measured at the central part of the models with a digital micrometer.

Fig. 2 Simplified illustration of composite resin cured by single laser beam scanning. (a) Formation of cured zone by a laser beam scanning. (b) Cross-sectional view of cured composite resin.

4) *Linear shrinkage after heat-treatment*

To evaluate the dimensional stability of the fabricated models, heat-polymerization was carried out for the models prepared by laser scanning. The ten-layered laminated models with the 10×10 mm beam scanning area as mentioned in 3) were made at the thickness of 1 mm. These models were fabricated by ten-time laminations of layers measuring 0.1 mm in thickness. After fabrication, the models were heat-polymerized for 2 hours in an electric furnace maintained at 150°C¹⁴⁾. The x and y directional shrinkage ratios were calculated from the dimensions measured using a profile projector before and after heating.

5) *Fabrication of composite resin full crown*

The composite resin crown was fabricated at the optimum experimental conditions deduced from processes 2), 3) and 4) using the data of the three-dimensional shape of crown (upper right first molar)¹⁵⁾.

4. *Fabrication of the functionally graded composite resin post and core and analysis of stress relaxation effect (2nd experiment)*

1) *UV curing composite resin*

The base resin with the initiator prepared in the 1st experiment was used here (Table 1). The filler of powdered glass fibers (fiber diameter: 13 μm, mean length: 70 μm) (Microglass, Nippon Sheet Glass Co., Ltd., Osaka, Japan) treated with the silane coupling agent was mixed with the base resin at the rate of 0, 9, 18, 27, 36, 45, 54 and 64 wt%, respectively.

2) *Measurement of elastic modulus of composite resin*

The elasticity of the composite resin with the uniform composition prepared in 1) was measured by 3-point flexural test using the universal testing machine (4204, Instron Corp., Canton, MA, USA) with a cross-head speed of 1.0 mm/min. The beam length between the two supports was 14 mm. Measurements of the flexural test were transferred to a personal computer with the sampling rate of 20 points/sec in real time, and the load-deflection curves were presented as graphs. Composite resin specimens were prepared in cylindrical shape with a length and diameter of 25 mm and 1 mm respectively¹⁶⁾. Six samples were cured by UV light for each filler content and were treated further by heat-polymerization at 120°C for 3 hours. This temperature was set lower than 150°C of the 1st experiment to reduce the influence of thermal deformation of the samples. The test was carried out at 23°C under dry conditions with 50% moisture. Young's modulus was calculated from the load-deflection curve using the equation $E=4Pl/(3\delta d^3)$, where P is flexural load, δ is deflection, l is gauge length, and d is wire diameter. Young's modulus of each composite resin was used for the FEM analysis in 2nd experiment.

3) *Fabrication of the functionally graded composite resin post and core*

The eight UV polymerized composite resin pastes of different filler contents were piled up to form the geometric shape of the post and core prepared by a personal

computer. The post was 9 mm in length, 2 mm in diameter at its apex with a taper of 10%, and the core was 8 mm in height. There was a 1 mm diameter hole inside the post and core to insert a prefabricated titanium post.

4) FEM analysis

A comparative analysis of stress distribution was carried out by FEM for the posts and a human tooth. The graphic pre- and post-processor (MSC.PATRAN, MSC. Software, Santa Ana, CA, USA) and the finite element analysis software (MSC. NASTRAN, MSC. Software, Santa Ana, CA, USA) were used for this purpose. The model assigned to the root of the upper central incisor with the component of the post and core bonded with resin cement was used for this simulation analysis. The produced model had 8988 elements and 9223 nodes.

Then the obtained model was subjected to a 10 N force directed at an angle of 125° to the main axis of the tooth¹⁷⁾. The force was applied to a palatal surface element which was 2 mm distant from the top of the core (Fig.3(a) and (b)).

The functionally graded post and other posts were compared in terms of the materials as follows.

- a) Metal post and core (ME post) of 12% Au-Pd-Ag alloy made by casting.
- b) Composite resin post and core (CR post): the composite resin post and core with a uniform filler content 64 wt% was fabricated by laser lithography with a prefabricated titanium post in the center.
- c) Functionally graded post and core (FG post): This was composed of composite resin with the filler content gradually changing from 0 wt% to 64

Fig.3 (a) The constraint condition of the model with the fixation on the root surface at 10 mm from the root apex (10 mm fixation). (b) The constraint condition of the model with the fixation on the root surface at 4 mm from the root apex (4 mm fixation).

Table 2 Mechanical properties of the materials used in stress analysis (FEM).

Material	Modulus of elasticity (GPa)	Poisson's ratio
Dentin	14.7	0.30
Resin cement	7.0	0.30
Au-Ag-Pd alloy	86.0	0.33
Prefabricated metal post (Titanium)	117.0	0.34
Resin composite (Filler content: 64wt%)	10.6	0.30

wt% in the longitudinal direction and the prefabricated titanium post in the center. The filler content was changed starting from 0 wt% at the apex of the post for every 1 mm thickness by eight steps.

The elastic moduli and Poisson's ratios^{17,18)} of the used materials are shown in Table 2. The elastic moduli at the different filler contents in the composite resin used for the FG post were obtained from the 3-point flexural test.

On the constraining attribute, two types of fixing conditions were set up to the FEM model; they were fixations of the root surface at 10 mm (10 mm fixation) and 4 mm (4 mm fixation) above the apex along the tooth axis as demonstrated in Fig. 3(a) and (b), respectively. The stress distribution was calculated inside the root and the post and core for the cases where the complex of the post and the radicular dentin was bended with the applied force under the above fixing conditions.

RESULTS

1. Cured width by single beam scanning

The shape of the single zone of a polymerized composite resin is shown in Fig. 4. The polymerized zone was observed by SEM from an oblique direction to show the stereoscopic view. The polymerized zone showed a hog-backed shape with a larger width compared with its depth. The zone had an irregular surface because of the existence of the fillers in the composite resin. The geometrical relation between the cured zone and laser beam is shown in Fig. 2(b).

The measured polymerized widths for different laser beam scanning conditions are demonstrated in Fig. 5. The widths were 0.38 mm at the scanning speed of 200 mm/sec, 0.31 mm at 250 mm/sec, 0.28 mm at 300 mm/sec, and 0.24 mm at 350 mm/sec. It is clear that the width was narrower with an increase of scanning speed. Although the laser spot diameter was 0.2 mm, all the cured widths were larger than this diameter. At the scanning speed of 200 mm/sec, the width was larger than the laser spot diameter by 0.18 mm. At the scanning speed of 350 mm/sec, which was the fastest speed in this experiment, the width was 0.04 mm larger.

2. Cured depth

The results of the measured cured depths are summarized in Table 3. They reflected the tendency that the slower scanning speed and the smaller scanning line interval

Fig. 4 SEM observation of polymerized zone of composite resin formed by single laser beam scanning.

Fig. 5 Change of cured zone width by laser scanning speed.

Table 3 Cured depth for each scanning condition.

Scanning interval (mm)	Scanning speed (mm/sec)				
	150	200	250	300	350
0.20	0.25	0.22	0.18	0.16	0.14*
0.30	0.21	0.17	0.14	0.11*	**
0.40	0.17	**	**	**	**

* Models were partly broken

** Models were completely broken

deepened the cured depth. Complete models failed to generate under the conditions of higher scanning speed with larger intervals that were 350 mm/sec and 300 mm/sec with an interval greater than 0.3 mm, 200 mm/sec with an interval of 0.4 mm, and 250 mm/sec with a 0.4 mm interval due to the separation of the cured zone or laminated layers from each other. Practically, the fabrication failed completely at the scanning speed of 200 mm/sec with a scanning interval of 0.4 mm because of the scanning interval wider than a cured width of 0.38 mm.

3. Linear shrinkage after heat-treatment

Fig. 6 shows the linear shrinkage ratio after the heat-polymerization treatment of the models fabricated by laser lithography. The dimensional changes of composite resin before and after the heat-polymerization ranged from about 0.3% to 0.6%. The faster scanning speed and the wider scanning interval increased the shrinkage percentage. A scanning speed of 50 mm/sec with a 0.2 mm interval was considered the best condition for polymerizing composite resin in this study because the total dose of the scanned laser beam was larger than the other conditions. In this condition the shrinkage percentage was about 0.3%. The x-directed scanning at 200 mm/sec speed with a interval of 0.36 mm resulted in the largest shrinkage percentage of 0.6%. Except the condition of 200 mm/sec and 0.36 mm interval, the shrinkage percentages of

Fig. 6 Linear shrinkage after heat polymerization treatment.

Fig. 7 The composite resin crown of fabrication by laser lithography ((a) : distopalatal view, (b) : mesiopalatal view).

the models ranged from about 0.3% to 0.4%.

4. Composite resin crown

Finally, the composite resin crown model was fabricated under the manufacturing condition determined at the scanning speed of 300 mm/sec with the interval 0.24 mm. The marginal area of the fabricated crown is shown in Fig. 7(a) and (b). The

Fig. 8 Elastic moduli of composite resin with different filler contents which are used for the component elements of the functionally graded post and core.

fabrication in the area of the crown's margin and outline was successful. The manual curving process on its occlusal surface is necessary because the surface was fixed on the stage for the initial fabrication by a laser lithography device.

5. Fabrication of the functionally graded composite resin post and core

The elastic moduli of each composite resin with different filler contents are shown in Fig. 8. An average elastic modulus was calculated from six specimens, and was used for the FEM analysis.

The functionally graded composite resin post and core fabricated by laser lithography is shown in Fig. 9(a) and (b). Fabrication of the post and core was completed precisely as shown in Fig. 9. The gradation aspect of the filler content was confirmed by its decreasing transparency from the apex to the cervical area of the post. The change in filler content in the post is demonstrated in Fig. 9(a). The prefabricated metal post was put into the post and core on trial before the completion of manufacturing (Fig. 9(b)), then, the prefabricated post was bonded inside with resin cement.

6. Stress analysis

The FG post was analyzed by FEM and compared with ME and CR posts. The von Mises' equivalent stresses in the post were plotted on the computer-generated color stress maps for each case. The stress in the element on the palatal surface of the post (as shown in Fig. 10) was demonstrated in graphs for further evaluation of the comparative differences in the stress distributions in each post.

Fig. 11(a) shows the computer-generated color stress maps for the constraint condition of the 10 mm fixation. The result of the ME post suggests that stress was conveyed toward the apex of the post from the point at the core where the external force was applied. The transferred stresses observed in CR and FG posts were

Fig. 9 (a) The fabricated functionally graded composite resin post and core. (b) A prefabricated metal post on the way to insert into the functionally graded composite resin post and core.

Fig. 10 Palatal surface of the post as the location of stress which is shown as a graph in Fig. 12

Fig. 11 Stress contour plots (von Mises' equivalent stress) in the post and core. (a) At 10 mm fixation. (b) At 4 mm fixation.

smaller than in the ME post. There was no significant difference in stress distributions between the FG and CR posts. The stress on the palatal surface is demonstrated in Fig. 12(a) and (b). Fig. 12(a) shows that the ME post had a larger stress compared to both of the CR and FG posts and this larger stress of ME post was significantly higher around the cervical area. The stress curve of the ME post culminated around 7.5 mm from the apex. The CR and FG posts showed similar stress levels and distributions. Stress peaks of both the CR and FG posts were much less

Fig. 12 Stress distribution on the palatal surface of the posts.
(a) At 10 mm fixation. (b) At 4 mm fixation.

than that of ME post. The stress became higher for both CR and FG posts toward the cervical area from the apex. Around the cervical area, there was a small difference in the stress between the CR and FG posts. For the direction toward the apex, the FG post showed a smaller stress distribution than the CR post. These curves came near each other around 2 mm distant from the apex.

Fig. 11(b) demonstrates the stress for the constraint condition of the 4 mm fixation. In the ME post, a larger stress concentration occurred around the apex. In the CR and FG posts, there were lower concentrated stresses. Fig. 12(b) shows that the peak value of stress that occurred around the apex was about 30 MPa for the ME post, and less than 10 MPa for the CR and FG posts. The FG post had a lower stress peak than the CR post around the apex of the post. The curve for the FG post had a saw-tooth appearance although there was no significant difference in the stress distribution toward the cervical region between the FG and CR posts, the stress peak of the FG post near the apex was about 30% lower than that for the CR post. The inclination of the curve for the FG post is slighter than that for the CR post.

DISCUSSION

1. CAD/CAM application of laser lithography for fabrication of composite resin prostheses

Laser lithography, a recently developed technique of rapid prototyping and manufacturing, can directly fabricate solid models from three-dimensional geometric measurements prepared by 3-D modeling software. The laser lithography device (SOUP400 GH) fabricates models using UV cured epoxy resin in industry. The resin had been improved for dimensional accuracy and is better adapted to fabrication by laser lithography. However, the epoxy resin cannot be used inside the human mouth in any

case because of the toxic properties. Only a few studies have been performed to fabricate prostheses using the epoxy resin, but during the course of those experiments the resin had been burned up after the fabrication. Therefore, in those studies, laser lithography was applied only to fabricate the original patterns of prostheses^{12,13}. Those studies did not utilize the full merits and advantages of the CAD/CAM system which would save labor and time to produce accurate models directly. In the present study, the direct fabrication of prostheses using dental composite resin was carried out. UDMA or Bis-GMA (2,2-bis[4-(3-methacryloxy-2-hydroxypropoxy)phenyl]propane) are free-radical polymerized resins commonly used in the field of dentistry. Laser lithography fabricates models by accumulating microthin slices of cured resin, so the suppression of the curing reaction due to oxygenic atmosphere must be considered. In this respect, UDMA is subjected less to the inhibition of curing reaction by oxygen⁹, and is more similar to quartz filler in refractive index than Bis-GMA²⁰. Thus UDMA was selected for the present study. In addition, for the application of the resin, the UV light polymerization initiator (BME) was added to the resin because the beam was a He-Cd UV laser with a wavelength of 325 nm.

2. Determination of optimum conditions for modeling performance by laser lithography (1st Experiment)

Laser beam scanning conditions were examined to obtain the optimum spatial resolution in polymerized width and depth of UV cured composite resin. This is important because the cured width and depth affect the dimensional accuracy of fabricated prostheses. The single zone width of cured composite resin measured in the present study was larger by a range from 0.4 mm to 1.8 mm than the diameter of the laser spot because of beam scattering caused by the filler. At a slower laser scanning speed, the radiation dose and scattered light became larger. If the increment of the cured width is known for each scanning speed condition, models can be fabricated accurately by the correction of geometric measurements for the offset to the incremental cured width.

Regarding the cured depth, the thickness of the laminated layer needed to be greater than 0.1 mm in a pilot study from the viewpoint of the expediency of leveling piled composite resin. The thinnest cured depth in this experiment was 0.11 mm at the scanning speed of 300 mm/sec with a scanning interval of 0.3 mm which met the above necessary conditions.

As the polymerization by laser scanning alone was suggested to be insufficient, the effect of post-polymerization heat treatment was studied. The method of heat polymerization was adopted from previous findings^{14,21}. The scanning condition at a scanning speed of 200 mm/sec with an interval of 0.36 mm resulted in the largest linear shrinkage ratio. This is because the unpolymerized monomer remained larger under this scanning condition. There was very little difference in linear shrinkage between the x and y directions. From the viewpoint of the accuracy and stability of model fabrication, the shrinkage of post-polymerization for the faster scanning speed should be restrained at the same level as the shrinkage ratio of the slower scanning

speed. The linear shrinkage ratio of approximately 0.4% even at the faster scanning speed, such as 300 mm/sec, was adequate for the fabrication as mentioned above.

The criteria for the determination of the optimum modeling condition were set from the points of (1) spatial resolution, (2) binding performance between the cured zones, and (3) the dimensional stability after fabrication. Although the condition of 350 mm/sec scanning speed resulted in the narrowest cured width as shown in Fig. 5, the models failed to fabricate because of the separation between the cured zones as demonstrated in Table 3. Taking the first and second criteria into account, the scanning speed of 300 mm/sec was considered as the optimum scanning speed. Regarding the third criteria, heat-treatment shrinkages of 300 mm/sec scanning speed at 0.2, 0.24 and 0.26 mm intervals were about 0.4%, which was similar to that of the largest light dose (scanning speed: 50 mm/sec, interval: 0.2 mm). Thus, the optimum modeling condition in this study was adopted as the speed of 300 mm/sec with the range of 0.20-0.26 mm interval from the point of fabrication efficiency.

3. Fabrication of composite resin full crown by laser lithography

The laser lithography device, SOUP400GH, was originally designed to establish models using liquid epoxy resin which can make a free level control by itself. If composite resin is applied, the viscosity of the composite resin paste disturbs the operation to add it onto the previous layer and to level its surface. Therefore, the establishments of new procedures were targeted in the present study. In this regard, we first developed the equipment as a sort of box construction around the stage to conserve the piled composite resin during the leveling operation. Second, we developed a technique to compress the composite resin with the glass mixing slab sandwiching a polyethylene film in between. The film creates better polymerization due to blocking off air and enables the continuous accumulation of cured slices. These procedures were considered as the most suitable for the present study. For future studies, a device which can automatically fabricate piling and leveling composite resin paste should be developed.

Although the fabrication of the composite resin full crown was attained in this study, the resolution of fabricating the crown remained at 0.28 mm in width and 0.10 mm in depth. According to Uchiyama *et al.*²²⁾, the suitability to fit a cast metal crown onto the abutment was in the range of 0.05-0.10 mm. In future studies, the resolution must be refined by decreasing the laser spot diameter below the necessary range to fabricate an esthetic composite resin full crown with sufficient accuracy.

4. Fabrication of functionally graded composite resin post and core (2nd Experiment)

In a clinical study, the cast metal post and core has been linked to the occurrence of root fracture due to stress concentrations²³⁾. Various contributing factors have been considered and a large number of investigations have already been performed for the better shape of post and core which could suppress root fracture. Composite resin as a material of post and core has been focused on in recent years because of its

closer elasticity to dentin than metal. However, the problem of root fracture has not yet been completely solved²⁴⁾. For further refinement, we generated a new system in the present study, that is, the functionally graded composite resin post and core system. This post and core has a lower elasticity modulus in a gradual fashion towards the apex with the purpose of stress deconcentration around the post. The post and core was fabricated by the lamination of layers changing the filler content of the composite resin in every layer with a thickness of 1 mm, thus, the gradually changing elasticity was successfully realized in the present study. In the 2nd experiment, powdered glass fibers were applied for the filler of composite resin. The anisotropic form of fillers has the effect to strengthen more than the isotropic form as reported by Kobayashi *et al.*²⁵⁾. The large size of the particles lowers the viscosity of the composite resin paste, which facilitates the laminating process.

The functionally graded post and core was fabricated by lamination of multiple composite resin layers. The incremental filling technique is well applied to composite resin restoration in clinical situations. Hence, the model fabricated by lamination of composite resin attained an acceptable strength clinically. In addition, the insertion of a prefabricated metal post reinforces the FG post and core. Thus, the strength of the FG post is considered as adequate for clinical use.

5. Stress analysis

Stress analysis was carried out for the evaluation of the stress deconcentration effect of the FG post. To this end, photoelastic stress analysis was accomplished and reported previously²⁶⁾. Photoelastic analysis confirmed that the stress concentrations around the apex of the CR and FG posts were lower than that of the ME post. There was also a difference in the stress distributions between the CR and FG posts, but it was not clear because the photoelastic resin has lower elasticity (about 3 GPa) than that of dentin (about 15 GPa). Hence, FEM analysis was performed for further investigation on the effect of the functionally graded material.

In FEM analysis, we examined the stress distributions of the posts under the conditions where a complex of the root and post was deformed by external force at two constrictive conditions. Stress concentrations of the CR and FG posts occurred in the area where the prefabricated metal post was inserted instead of the area around the post (Fig. 11(a)). The prefabricated metal post was inserted into the composite resin post and core since the fracture strength of the composite resin by impact force was much lower than the compressive strength. So, it is suggested that the result of those stress distributions was acceptable desirable in the light of reinforcing the post and core made of composite resin. However, in contrast, the insertion of the prefabricated metal post may induce higher sensitivity to root fracture due to its high elasticity⁸⁾. According to Assif *et al.*²⁷⁾, the stress is transferred on the surface part of the tooth when functional external force is applied to a vital tooth. On the other hand, the root center where a post is inserted remains neutral in terms of stress concentration. If the post with a high elasticity is inserted into the root canal after endodontic treatment, then a high stress concentration should

occur around the post by the external force.

At the 4 mm fixation, the ME post caused a high stress concentration around the apex of the post. In contrast, the CR and FG posts using composite resin could substantially relax the stress concentration, which contributed to the suppression of root fracture probability. The use of the FG post further dropped the peak stress around the apex by 30% of the CR post. If functional force is applied to a tooth repeatedly over long term, the effect of the deconcentration by the FG post would provide a significant influence on the prevention of fatigue fracture. Therefore, it is suggested that the FG post can relax the stress concentration around the apex of the post more efficiently than the CR post. The saw-teeth appearance of the FG post (Fig. 12(b)) was caused by the stress concentration due to the boundary condition with an abrupt change in the elasticity of the composite resin. This appearance could be improved by the formation of thinner gradient layers.

CONCLUSIONS

1. The optimum modeling condition of 300 mm/sec scanning speed and 0.2-0.26 mm scanning interval was determined from the criteria of the spatial resolution, the binding performance between the cured zone, and the dimensional stability of the fabricated model.
2. Laser lithography could be applied for the fabrication of composite resin prostheses as full crowns.
3. The functionally graded composite resin post and core, which showed a gradual change in elasticity in the post, was fabricated successfully by laser lithography.
4. The FEM analysis of the functionally graded post and core demonstrated the effect of its stress relaxation at the apex, which could contribute to reduce root fractures due to stress concentrations. This will develop to the individual post and core with the optimum gradience for each endodontically treated tooth in the future.

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