Zirconia-reinforced dental restorations

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CHAPTER 4

Is the resin composite an alternative to make permanent fixed dental prosthesis?

- a study of fiber or zirconia-bar-reinforced composite fixed dental prosthesis-
4.1 Abstract

Objectives: The aim of this study was to compare conventional permanent fixed dental prosthesis (FDP) with plain resin composite FDP and two kinds of reinforced resin composite FDPs, at the respect of load-bearing capacity and stress distribution by finite element analysis (FEA).

Methods: Forty FDPs were divided into five groups (n = 8) by material: plain resin composite (Filtek Z250, 3M ESPE), fiber-reinforced resin composite (FRC) (everStick, Stick Tech/Filtek Z250, 3M ESPE), zirconia-bar-reinforced resin composite (ZRC) (Cercon base, Degudent/Filtek Z250, 3M ESPE), porcelain fused to metal (PFM), and porcelain with zirconia core (LAVA, 3M ESPE). All the FDPs were loaded until failure at the speed of 1 mm/min, with the testing ball (d = 12mm) in the middle of the occlusal surface of the bridge pontic. The load at failure was reported as the load-bearing capacity, and the work to fracture (Wf) was calculated as the area under the load/displacement curve. The FEA was performed using the load of failure as input. One-way ANOVA was used to analyze the load-bearing capacity and Wf.

Results: The average load-bearing capacity for FRC FDPs was 1,494 (148) N, and for ZRC ones was 1,409 (213) N. Both were significantly higher than the average of the other three groups (P < 0.05). The mean Wf of FRC FDPs was 1,128 (352) N·mm, which was significantly higher than the other four groups (P < 0.05). The FEA results showed that the bottom of the connectors was the weakest part of the three resin composite FDPs.

Significance: Resin composite FDPs especially the reinforced ones could be considered as an alternative to conventional permanent FDPs.
4.2 Introduction

Nowadays, metal-free materials are increasingly preferred for dental restorations, since they have improved biocompatibility and better aesthetic properties. The best-known metal-free material is ceramic, and the most commonly used core material for all-ceramic restorations is zirconia [1]. However, there are still some problems with all-ceramic restorations, such as chipping and debonding [2].

Resin composite is another metal-free material which has been used in dentistry as a filling material and a temporary restorative material for the last decades. Recently, resin composites have become stronger and more resistant to wear, making it possible to make permanent crowns and short dental bridges [3]. Resin composites can be further reinforced with all kinds of fibers, such as polyethylene, carbon, and glass fibers. The fibers inside the composites can improve the fracture resistance of composite fixed dental prosthesis (FDP), so that the FDPs can withstand higher oral forces [4-7]. Because of the increased success rate, fiber-reinforced resin composites (FRCs) are gradually being adopted for use in long-term restorations, such as FPDs [8-13]. However, the fibers are not easy to handle and other methods to reinforce the composite restorations have rarely been reported. Fischer et al. reported improvements of the load-bearing capacity of polymer-based dental bridges by reinforcing ceramic bars [14], which can also be considered as another way to reinforce common resin composites.

Because resin composite FDPs have seldom been compared to metal based FDPs or all-ceramic FDPs in one study, it is still unclear whether they are as strong as those conventional alternatives. Previous studies have also defined failures of composite restorations in different ways [15-17], which makes the comparison between studies more difficult.

Since mechanical failure is caused mainly by excessive stress or deformation, a complete understanding of the stress distribution in an FDP is particularly important. To precisely calculate the stress distribution, finite element analysis (FEA) can be applied, and it is regarded as the most representative quantitative analysis to model FDPs [18, 19]. Once the fundamental finite element model has been verified appropriately, it is conveniently to change relative parameters of the model, such as geometries, materials properties and boundary conditions [18].

The aim of this study was to compare plain resin composite FDPs and two kinds of reinforced composite FDPs to conventional permanent FDPs in vitro. We used the load-bearing capacity, i.e. load at failure, and the work to fracture as the
testing parameters. FEA was used to evaluate the stress distribution within the three groups of resin composite FDPs.

4.3 Materials and Methods

The left lower first premolar and the second molar (35 and 37) were standardly prepared as the abutment teeth, with a 1 mm chamfer and rounded occlusal edges. The mold of these two prepared abutment teeth were made by a transparent condensation-cure-silicone impression material (Mold Max 15T, Smooth-on Inc., Easton, PA, USA). After that, a flowable resin composite (Filtrek Supreme XT, 3M ESPE, St. Paul, MN, USA) was injected to the impression mold to make forty pairs of duplicated resin composite abutment teeth. Each abutment tooth was first cured within the mold by a curing light (Astralis 10 curing, Ivoclar Vivadent, Schaan, Liechtenstein) for 20 s from six directions, and then in a light oven (100 Lumamat, Ivoclar Vivadent, Schaan, Liechtenstein) for 3 min. For total polymerization, the abutment teeth were then taken out of the mold, and placed into the light oven again for another 25 min. All the abutment teeth were stored in 37°C distilled water for 1 day.

Porcelain fused to metal FDPs and all-ceramic FDPs: Eight identical Porcelain fused to metal (PFM) FDPs and eight all-ceramic FDPs (LAVA, 3M ESPE, USA) were made according to manufacturers’ instructions. The dimensions of the connectors were about 9mm². The impression mold of the standard FDP was made by a transparent vinyl polysiloxane impression material (Memosil 2, Heraeus Kulzer GmbH, Germany) which was embedded in a putty impression (Provil novo, Heraeus Kulzer GmbH, Germany) (Figure 4.1). The shape of the other PFM and all-ceramic FDPs were duplicated using the same silicon mold to ensure the geometries of all FDPs were identical.

Plain resin composite FDPs: Eight plain resin composite FDPs were made of Filtek Z250 (3M ESPE, USA) using a silicone mold of the PFM FDPs to ensure identical geometry (Figure 4.1). The resin composite was placed in the mold in layers of 1.0 to 1.5 mm, and polymerized with Astralis 10, curing for 20 s each layer. After removal from the mold, the FDPs were cured in a light oven (100 Lumamat, Ivoclar Vivadent, Liechtenstein) for 25 min. They were stored in 37°C distilled water for 1 day and polished with composite polishing discs (Sof-Lex Finishing and Polishing System, 3M ESPE, USA) before cementation.
Fiber-reinforced resin composite FPDs: Eight Fiber-reinforced resin composite (FRC) FDPs were made of the same resin composite Z250, but reinforced with glass fiber (EverStick, Stick Tech Ltd., Finland). During the procedure, the same silicone mold was used as for the plain composite group (Figure 4.1) and the fibers were placed as near the bottom of FDP as possible. The glass fibers are oriented in unidirection and placed longitudinally along the bridge with a thickness about 1mm [19, 20]. The same polymerization, storage and polishing protocol was used as for the plain composite group.

Figure 4.1 Photograph of the model for producing the plain resin composite, FRC and ZRC FDPs and the experimental set-up in the universal testing machine.

Figure 4.2 The FEA model with the zirconia bar and fiber inlay
**Zirconia-bar-reinforced resin composite FPDs:** In this group, eight zirconia bars were made (Cercon base 38 colored, DeguDent GmbH, Germany), and sintered in an oven (Cercon Heat, DeguDent GmbH, Germany) according to the manufacturer’s program. After the firing procedure, the zirconia bar had a final dimension of \((8.0 - 16.5) \times 3 \times 3\) mm (Figure 4.2). All the eight zirconia bars were sandblasted for 10 s on all surfaces, by 50 µm Al\(_2\)O\(_3\) at a distance about 10 mm (Sand Storm, Vaniman Manufacturing CO., CA, USA) and ultrasonically cleaned with distilled water for 10 min. The cleaned bars were pretreated with Clearfil SE bond (Kuraray Co. LTD, Japan), before they were embedded in the uncured Filtek Z250 composite bridge. All the eight Zirconia-bar-reinforced resin composite (ZRC) FDPs were finished, polymerized, stored and polished according to the same protocol as for the plain composite group.

**Cementation:** All the FDPs were cemented onto the abutment teeth with a dual-cured self-adhesive universal resin cement (RelyX Unicem, 3M ESPE). The cement was also cured by a curing light (Astralis 10, Ivoclar Vivadent, Liechtenstein) for 20 s from each tooth face; during this curing procedure a constant load of 50 N was used. The cemented FDPs with abutment teeth were stored in distilled water at a temperature of 37°C for 24 hr.

**Load test:** The FDPs were placed in a plastic mandibular alveolar model. To mimic the flexibility of the periodontal ligament, a thin layer of polyether impression material (Impregum F, 3M ESPE, USA) was used between the abutment roots and the model. Two hours later, the load at failure was determined by a universal testing machine (Instron 6022, Instron Corp., MA, USA; Figure 4.1) at the loading speed of 1mm/min. The compressive load was applied on the center of the pontic occlusal surface, using a stainless steel semi-ball (\(d = 12\) mm). The load (N) at the failure of the bridge was recorded as the load-bearing capacity. The work to fracture (\(W_f\)), which represents the total amount of energy required to break a FDP, was calculated as the area under the load/displacement curve [21], using data analysis and graphing software Origin Pro 8 (Origin Lab Corp., Northampton, MA, USA).

**Finite element analysis:** For the three resin composite groups, we created three-dimensional FEA simplified models of the test set-up. The finite element modeling was carried out by FEMAP software (FEMAP 10.1.1; Siemens PLM software, Plano, Texas, USA), while the analysis was done with NX Nastran software (NX Nastran;
Siemens PLM Software, Plano, Texas, USA). The models consisted of the layer of the jaw, the periodontium, elements 35 and 37, and the FDP with and without inlay (Figure 4.2). The reinforcement of glass fiber was shown as glass fiber inlay, and the zirconia bar was shown as zirconia inlay. The material properties used for the analysis are summarized in Table 4.1. The models were composed of 67,778 parabolic tetrahedron solid elements. To simulate the loading ball, the nodes in the centre of the pontic occlusal surface were loaded (Figure 4.4), with the experimentally found values as shown in Table 4.2. The nodes at the bottom of the jaw were fixed, with no movement being allowed in any direction.

**Table 4.1** The material properties used in the FEA.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (MPa)</th>
<th>Poisson ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jaw</td>
<td>PMMA</td>
<td>1,963</td>
</tr>
<tr>
<td>Periodontium</td>
<td>Impregum</td>
<td>0.35</td>
</tr>
<tr>
<td>FDP</td>
<td>Filtek Z250</td>
<td>12,000</td>
</tr>
<tr>
<td>Glass fiber inlay</td>
<td>Glass fiber</td>
<td>39,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12,000</td>
</tr>
<tr>
<td>Glass fiber vertically</td>
<td></td>
<td>12,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>12,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>39,000</td>
</tr>
<tr>
<td>Zirconia inlay</td>
<td>Zirconia</td>
<td>210,000</td>
</tr>
</tbody>
</table>

Statistics: The values obtained for the load-bearing capacity and \( W_f \) from each group were analyzed by one-way ANOVA, and the Turkey test was adopted for the post-hoc test. The statistics were done with software SPSS 18.0 (SPSS Inc., Chicago, Illinois, USA) at a significance level of \( \alpha = 0.05 \).

**4.4 Results**

The mean load-bearing capacities, *i.e.* load at failure, were summarized in Table 4.2. The two reinforced resin composite groups resulted in significantly higher \( (P < 0.05) \) load-bearing capacities than the other three groups. The results of \( W_f \) were also
summarized in Table 4.2. The mean $W_f$ of the FRC FDPs was 1,128 (352) N·mm, which was significantly higher ($P < 0.05$) than the other four groups.

**Table 4.2** Results of load-bearing capacity (in N) and work to fracture (in N·mm) and their standard deviation in parentheses.

<table>
<thead>
<tr>
<th>Group</th>
<th>Load-bearing capacity*</th>
<th>Work to fracture*</th>
</tr>
</thead>
<tbody>
<tr>
<td>PFM</td>
<td>733 (179)$^a$</td>
<td>286 (109)$^A$</td>
</tr>
<tr>
<td>Lava</td>
<td>868 (175)$^{a,b}$</td>
<td>341 (136)$^A$</td>
</tr>
<tr>
<td>Z250</td>
<td>1007 (83)$^b$</td>
<td>404 (54)$^A$</td>
</tr>
<tr>
<td>Z250 + zirconia bar</td>
<td>1409 (213)$^c$</td>
<td>457 (143)$^A$</td>
</tr>
<tr>
<td>Z250 + everStick</td>
<td>1494 (148)$^c$</td>
<td>1128 (352)$^B$</td>
</tr>
</tbody>
</table>

*values with identical letters indicate no statistically significant differences ($P > 0.05$)

The main failure patterns for the five groups were shown in Figure 4.4. In the PFM group and LAVA group, the main failure pattern was delaminating. In the plain resin composite group and the ZRC group, the main failure occurred at the connector part. The fractures in the FRC group were always along the longitudinal fiber direction.

**Table 4.3** The highest maximum principle stress (in MPa) in the resin composite FDPs with and without inlay.

<table>
<thead>
<tr>
<th></th>
<th>Model without inlay (load=1007N)</th>
<th>Model with zirconia inlay (load=1409N)</th>
<th>Model with glass fiber inlay (load=1007N)</th>
<th>Model with glass fiber inlay (load=1494N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In the composite bottom connector</td>
<td>109</td>
<td>105</td>
<td>104</td>
<td>152</td>
</tr>
<tr>
<td>In the composite pontic bottom</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In the glass fiber inlay</td>
<td></td>
<td></td>
<td></td>
<td>280</td>
</tr>
<tr>
<td>In the zirconia inlay</td>
<td></td>
<td></td>
<td></td>
<td>215</td>
</tr>
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</table>

The FEA results were shown in Table 4.3 and Figure 4.4. The highest stress in the composite was around 105 MPa, always at the bottom of the mesial connector,
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except the model with glass fiber. When the FRC model was loaded at 1,494 N, which was the average fracture load of the FRC group, the highest stress at the mesial connector bottom was 152 MPa, and the highest stress at the bottom of the pontic was 114 MPa (Table 4.3 and Figure 4.4). The highest stresses in the glass fiber and zirconia inlays are also reported in Table 4.3.

![Figure 4.3](image_url)

Figure 4.3  The main failure mode of each group: a) PFM; b) Lava ceramic; c) plain resin composite; d) fiber-reinforced resin composite; e) zirconia-bar-reinforced resin composite.
Figure 4.4  The highest maximum principle stress (in MPa) in the composite for the three models and for the model with glass fiber at the bottom of the pontic. Stress distribution of the mesial connector is illustrated from a—d, and the stress of the pontic bottom for d is showed in part e. a) Model without inlay at the average fracture force 1,007 N; b) Model with zirconia inlay at the average fracture force of 1,409 N; c) Model with glass fiber inlay at the load of 1,007 N; d) Model with glass fiber inlay at the average fracture force 1,494 N; e) Bottom pontic stress of Model d.

4.5 Discussion

This study attempted to test FPDs made of various materials in the same testing set-up, so that the results achieved by different materials could be compared. It is noteworthy that PFM FPDs were less strong than all the other materials, and the load-bearing capacity was only 733 N, which is also lower than most results from other studies [22, 23]. From a review of Kelly [24], the size and stiffness of the loading ball could influence the contact stress, which can lead to different results of same material. The loading ball used in this study was stiff and the veneering porcelain is extremely brittle, which can cause a contact damage at quite a low force. The main failure mode of PFM group was the fracture of veneering porcelain and its delaminates from the metal base. This phenomenon supports the clinical experience that delaminating, chipping or porcelain fracture are the most common (repairable) complains of the PFM restorations [2, 25-27].
Similarly, the load-bearing capacity of Lava group was 868 N, which seems also lower than the three resin composite groups. Earlier studies report that the load-bearing capacity of zirconia all-ceramic FPDs (veneered) ranged from 651 to 2,251 N [23, 28-31]. This large range could be caused by the different testing methods. Besides the differences of the loading balls, some of the studies did not simulate the periodontal ligament [23], so that there was no movement of the abutment teeth during loading and resulted in a higher load. This can lead to an overestimation of the load-bearing capacity of the restorations [32, 33]. Another important factor was the abutment material; several materials were used, such as human teeth [30, 34], metal [23, 31], polymer and resins [29]. When soft materials like human teeth, polymer or resin composites were used as abutments, the load-bearing capacity was usually lower than 1,000 N [29]. Previous studies showed that resins had very similar mechanical properties to those of natural tooth, giving support close to that provided by nature [35-38]. The higher the elastic modulus of the supporting material, the higher could be the load to failure [39]. If a rigid support was used, it could hinder the movements of the abutment teeth, and led to an unrealistic fracture load [23, 29, 40].

Although the core material of zirconia is a rather strong material, the Lava all-ceramic FDPs fractured at both the porcelain veneer and the zirconia framework. Sundh et al. reported that the load necessary to fracture the zirconia frameworks was higher than veneered ones [31]. They also found that when the frameworks were subjected to heat-treatment, same as the veneering procedure but without the actual veneer porcelain, still exhibited significantly lower fracture resistance compared to the specimens as delivered after machining. In other words, heat-treatment and/or veneering could affect mechanical properties of zirconia framework and make it weaker [31].

This study showed a higher load-bearing capacity of around 1,500 N in the two reinforced resin composite groups. Due to the various composite patterns, fiber designs, and test set-ups, the load-bearing capacity results for posterior FRC-FPD ranged widely from 530 N to 2,354 N [4, 10, 41-44]. However, our findings agreed with earlier studies showing that the FRC-FPDs always have a higher load-bearing capacity than the plain composite restorations [4, 10, 41-44]. Our simplified ZRC FPD showed higher load-bearing capacity than the results of Ficher’s T-bar group which was 918 (238) N, and close to their I-bar group which was 1,603 (327) N [14]. However, both their T or I-bars should be shaped in an industrial process by a professional ceramic machining machine with diamond charged tools. Our bar shape
was simplified, so it is easy to make the bars by a normal sawing machine and customize them by diamond burs and can make the most use of the material.

The main failure mode of the plain composite group and the zirconia-bar-reinforced group was the facture at the connector part. However, in the fiber-reinforced group, the main failure type was the fracture at the fiber/resin interface, mainly along the longitudinal fiber direction in the pontic. Although there were some FDPs occurring connector fracture in the composite part, the glass fiber was still linking the two separated composite parts together. In previous studies, the similar main failure mode was found at the interface between the fibers and the resin composite matrix [4, 41-43, 45], though sometimes in the connectors [17, 46, 47]. One explanation to this result is that the fibers are able to slow down or arrest the crack propagation, so that the fiber reinforcement can minimize the instantaneous and catastrophic failures, while they are additionally linking fractured specimen fragments [20]. Thus, for the specimens without the fiber reinforcement, the failures are catastrophic, resulting in complete fracture from the weakest point, usually at the connectors [11, 46]. However, it was reported that fractures could also start at the loading point [4, 45, 48], which was also observed in our study. For the FRC group, the glass fibers were placed as low as possible to the pontic bottom, according to former studies which showed that placing the reinforcement at the tension side was the most effective position to enhance the fracture load [20].

The FEA in this study showed that in all the composite FPDs, the highest stress was at the bottom of connectors (Figure 4.4), which belongs to the tension side. It was reported also by other FEA studies that in the posterior 3-unit FRC FPDs, tensile stress concentrations located at the bottom of the pontic and the connector regions [14, 19, 49-51]. They are considered as the weakest region in composite FDPs [46], and inadequate reinforcement in these regions will lead to clinical failure [52]. In our FEA study, the highest stress of the composite model without inlays was 109 MPa, which was quite close to the tensile fracture strength of Z250 used in this study. However, when the composite model with fiber inlay was loaded at 1,494 N, i.e. the mean final fracture load of the FRC FPDs, the highest stress in the composite was 152 MPa, at the bottom of mesial connector. This stress is considered extremely high, which implies that cracks may already have happened at this part. Furthermore, in the same model and load input value, the maximum stress at the bottom of pontic was 118 MPa, which was also higher than fracture strength and could cause another crack. When the same model was loaded at 1,007 N, i.e. the mean final fracture load of the plain composite FPDs, the highest stress in the composite reduced to 104 MPa, also at the bottom of
mesial connector. This stress was similar to the results from the plain composite model and the model with zirconia inlay.

From the results above, we can assume that a first crack occurred under a load of 1,007 N at the connectors of the FRC FDP. However, the fibers were able to stop this crack and the FDP resisted to a higher load until the final fracture happened. When the input load increased to 1,494 N, the stress at the connector increased to 152 MPa, which was computed under the assumption that the composite was still a sound bulk. Thus, the value of 152 MPa could not represent the real stress on this condition. The real stress concentration changed inside the glass fiber, with a value of 280 MPa. In addition, with the increase of the input load, the maximum principle stress at the bottom of the pontic became as high as 114 MPa, which was also higher than the fracture strength of the resin composite. Such a high stress also caused cracks from the bottom part and finally led to the fracture along the fiber and resin interface. Accordingly, at least one notch was found at each load/displacement curve of the fiber-reinforced group, which indicated that a crack could have happened at that moment. On the other hand, the FRC FDP had the highest work to fracture ($W_f$) of the five testing groups, while the other four groups got quite low values. The higher $W_f$ means more energy is required to break the same 3-unit posterior FDP [53]. By regarding the setup we tested as a whole system, we could consider the value of $W_f$ as a parameter of the apparent system toughness [53]. The higher the toughness the more difficult for cracks to grow, and the more difficult it is to damage a material [54]. It’s quite understandable that the PFM and Lava FDPs were very brittle because of the veneering porcelain, as they both had a main fracture model of delaminating. The plain composite and ZRC FDPs got higher $W_f$, but not significant. This may be explained that the zirconia itself is also a kind of brittle ceramic, and it cannot stop the crack easily, and the improvement of the toughness was not effective.

In favor of using the initial load at failure is that the results can be used as input for the FEA calculations. But the limitations of this type studies is the use of simplified in vitro models and the lack of fatigue and exposure to the oral environment. Studies from other researchers showed that long term water storage [55] and cyclic loading will decrease the load bearing capacity of FRC FPDs [56]. One explanation is that the artificial aging like thermal cycling or cyclic loading can reduce the fracture strength of resin composites [57-59]. Another reason is that artificial aging may influence the cement layer and decrease the bond strength of the FPDs [60]. Meanwhile, previous study also showed that fatigue can affect the performance of ceramics and decrease the fracture load of all-ceramic restorations [30, 61-66]. However, some other studies
showed that artificial aging did not affect the fracture load of all-ceramic restorations [31, 67]. As a result, it seems that we need further study on the comparison of different kinds of FPDs after fatigue.

According to earlier publications, the mean maximum biting force ranges from 365 to 965 N [68-76], with the highest bite force in the first molar region. It is therefore reasonable to assume that an initial load-bearing capacity of 1,000 N is required for a favorable clinical prognosis of posterior FDPs [64]. In this respect, all the three types of resin composite FDPs tested in this study are clinically acceptable, and both the zirconia bar reinforcement and the fiber reinforcement are effective. However, cautions must be exercised when extrapolating laboratory data to clinical situations. From a systematic review, there is no single in vitro test that can predict clinical performance in prostheses [77]. As stated above, one should realize that the effect of fatigue on metals, zirconia and composites is completely different. The strength of composites can decrease with 50% or more after 10,000 cycles [78], while the effect of fatigue on metals and zirconia is less pronounced [79]. This might explain why the clinical success of resin composite FPDs is lower compared to their PFM and zirconia analogues. This indicates that there is a need for more fatigue resistant composites.

4.5 Conclusion

Based on the parameters investigated in this study, we can conclude that the initial mechanical property of plain composite FDPs may be as well as that of conventional FPDs. The performance could be even better if they are reinforced by glass fiber or zirconia bar, as long as the load-bearing capacity and the work to fracture are regarded. The resin composite FDPs can be considered as an alternative to conventional FPDs, especially when they are reinforced.

4.6 Reference

[2] Tan K, Pjetursson BE, Lang NP, Chan ESY. A systematic review of the survival and complication rates of fixed partial dentures (FPDs) after an observation
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Alternative permanent fixed dental prosthesis


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