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Fatigue resistance of all-ceramic fixed partial dentures – Fatigue tests and finite element analysis

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ABSTRACT

Objective. To estimate the fatigue resistance of a new translucent zirconia material in comparison to lithium disilicate for 3-unit fixed partial dentures (FPDs).
Methods. Eighteen 3-unit FPDs (replacement of first upper molar) with a connector size of 4 mm × 4 mm were dry milled with a five-axis milling machine (Zenotec Select, Wieland, Germany) using discs made of a new translucent zirconia material (IPS e.max ZirCAD MT, Ivoclar Vivadent). Another 9 FPDs with a reduced connector size (3 mm × 4 mm) were milled. The zirconia FPDs were sintered at 1500 °C. For a comparison, 9 FPDs were made of IPS e.max Press, using the same dimensions. These IPS e.max Press FPDs were ground from a wax disc (Wieland), invested and pressed at 920 °C. All FPDs were glazed twice. The FPDs were adhesively luted to PMMA dies with Multilink Automix. Dynamic cyclic loading was carried out on the molar pontic using Dyna-Mess testing machines (Stolberg, Germany) with 2×10^6 cycles at 2 Hz in water (37 °C). Two specimens per group and load were subjected to decreasing load levels (at least 4) until the two specimens no longer showed any failures. Another third specimen was subjected to this load to confirm the result. All the specimens were evaluated under a stereo microscope (20× magnification). The number of cycles reached before observing a failure, and their dependence on the load and on the material, were modeled, using a Weibull model. This made it possible to estimate the fatigue resistance as the maximum load for which one would observe less than 1% failure after 2×10^6 cycles. In addition to the experimental study, Finite Element Modeling (FEM) simulations were conducted to predict the force to failure for IPS e.max ZirCAD MT and IPS e.max Press with a reduced cross-section of the connectors.
Results. The failure mode of the zirconia FPDs was mostly the fracture of the distal connector, whereas the failure mode of the lithium disilicate FPDs observed to be the fracture of the connectors or multiple cracks of the pontic. The fatigue resistance with 1% fracture probability was estimated to be 488 N for the IPS e.max ZirCAD MT FPDs (453 N for repeated test), 365 N for IPS e.max ZirCAD MT FPDs with reduced connector size and 286 N for the e.max Press FPDs. All three IPS e.max ZirCAD groups statistically performed significantly

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better than IPS e.max Press ($p < 0.001$). On the other hand, no significant difference could be established between the two IPS e.max ZirCAD MT3 groups with a 4 mm × 4 mm connector size ($p > 0.05$). The allowable maximum principal stress (σ_{max}) which did not lead to failure during fatigue testing for IPS e.max ZirCAD MT3 was calculated between 208 MPa and 223 MPa for FPDs with 4 mm × 4 mm connectors for 2×10^6 cycles. This value could also be verified for the FPDs of the same material with 3 mm × 4 mm connectors. On the other hand fatigue strength in terms of σ_{max} at 2×10^6 cycles of IPS e.max Press was calculated to be between 78 and 90 MPa.

Significance. The fatigue resistance of the translucent zirconia 3-unit FPDs was about 60–70% higher than that of the lithium disilicate 3-unit FPDs, which may justify their use for molar replacements, provided that a minimal connector size of 4 mm × 4 mm is observed. Even with a limited number of specimens ($n = 9$) per group it was possible to statistically differentiate between the tested groups.

1. Introduction

If a tooth in the posterior region is missing, a three-unit fixed-partial denture (FPD) is the treatment of choice provided that the patient wants to have the missing tooth replaced due to esthetical and/or functional reasons and provided that the adjacent teeth had already been restored with crowns or fillings; otherwise an implant can be an option [1,2].

A variety of different materials are available for three-unit FPDs. The gold standard is still porcelain fused to metal (PFM) with survival rates of about 94% over a period of 5 years [3]. However, many all-ceramic options are available, including veneered zirconia, monolithic zirconia, monolithic lithium disilicate, and glass-infiltrated aluminia. These options tend to have lower survival rates compared to PFM, as a meta-analysis has shown [3]. In this meta-analysis, however, monolithic lithium disilicate FPDs were mixed with veneered lithium disilicate FPDs, with the latter being associated with a higher failure rate including fractures of the connectors and chipping of the veneering. In some cases, the fractures occurred in connectors that did not meet the minimum requirements stipulated for the connector size (4 mm × 4 mm). Three studies evaluated the efficacy of monolithic lithium disilicate FPDs to replace the first molar or to have the first molar as distal FPD retainer [4–6]. As all three studies have shown high failure rates for this indication (up to 15% after 4–10 years), the use of lithium dislicate for FPDs is restricted to the second premolar as the most distal FPD retainer.

Clinical trials have proven that layered zirconia FPDs are associated with significantly more chippings of the veneering ceramic than PFM [3,7,8]. With changes of the processing procedure (slow cooling) and the design of anatomically supported veneers, the chipping frequency decreased, as a more recent review has indicated [9]. Recently, translucent zirconia materials that do not require an additional veneering ceramic have been brought to the market. It has been assumed that there is an increased wear of intact natural enamel antagonists due to the hardness of the zirconia material when opposed to enamel. Clinical studies, however, have not confirmed this assumption [10–12].

It appears insufficient to rely only on typical physical parameters, such as flexural strength or fracture toughness, to predict the clinical performance of newly developed all-ceramic materials for FPDs. Monotonic loading of FPDs to failure in a universal testing machine is also an inadequate test method to predict the clinical performance [13].

Already in the late nineties, Kelly demanded that all-ceramic materials tested in the laboratory should produce failures that are comparable to those in clinical situations [14]. He identified several important factors that are essential to carry out meaningful laboratory tests: (1) Contact area of stylus with the specimen, (2) clinically relevant crowns cemented on a defined substrate, (3) cyclic loading, and (4) wet conditions. Therefore, laboratory tests should include the testing of standardized FPDs that are luted to an adequate substrate and subjected to dynamic loading in a wet environment.

A reasonable cyclic or dynamic loading test should be performed and the results should be compared to clinically proven materials. However, which dynamic test is reasonable and adequate? Fatigue tests can be performed on standardized, rectangular specimens [15] or on anatomically designed specimens [16]. When using anatomically designed specimens, it is obviously not sufficient to mount FPDs in a chewing simulator and load them with a constant force of 50 N or 100 N as this is done in many laboratory studies [17–19]. As mostly no failure occurred at this load level, the specimens were subjected afterwards to monotonic loading in a universal testing machine to determine the fracture force. The claim was that the specimens had been preloaded before in a clinically relevant manner.

Fatigue resistance is defined as the weakening of a material by repeated loading and unloading causing progressive and localized structural material damage [20]. A crucial parameter is the force with which the specimens are loaded. Either higher forces than those that occur in the human dentition are applied to accelerate the simulation process or forces that are similar to those in the human dentition are applied, however, with a much higher number of cycles. Another approach is to test specimens at different load levels to determine what is known as fatigue resistance by submitting clinically relevant specimens to a range of different descending loads with a suf-