A focus on zirconia: an in-vitro lifetime prediction of zirconia dental restorations
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Chapter 10

Summary and conclusions
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Zirconia has been used for about ten years for the fabrication of dental restorations. The fast development of material and fabrication techniques has promoted zirconia restorations in this short time period as alternatives for metal-based fixed partial dentures (FPDs). As a consequence of this rapid development and as a reaction to rapidly growing markets, shortcomings may appear, and users have to learn to cope with the application. This thesis has been performed to improve the knowledge about zirconia ceramics. Clinical studies and in-vitro simulation provide information regarding “where the shoe pinches,” and dental material science responds by attempting to find solutions for the problems.

Chapter 1 presents an overview on zirconia and its dental applications. Zirconia is reported to be a high strength material, with promising properties in the fields of strength and biocompatibility, but it also has limitations in terms of aesthetics, bonding, and deterioration. The available clinical data reveal that zirconia cores provide high strength, and fractures have only been reported in isolated cases. The current major reason for failures of zirconia restorations is the chipping of the veneering ceramic in about 10-15% of the restorations. Research has focused on the reasons for chipping, and therefore, chapter 2 presents data from investigations of the basic properties of the zirconia core material and its glass-ceramic veneering. This part of the thesis shows that the individual steps of heat treatment during glass-ceramic veneering have only a small influence on the storage modulus. The application of the veneering changed the modulus of the specimens and reduced the overall modulus of the combined zirconia glass-ceramic specimen significantly. A constant thickness of the veneering may therefore help to improve the performance of FPDs. The influence of the loading side, whether the treatment was located on the tensile side or on the pressure side, was of interest when the specimens were steam cleaned, annealed, or stored. This is of interest for the laboratory fabrication of dental restorations, especially FPDs. Further studies should deal with the question of whether dynamic mechanical analysis (DMA) allows for the investigation of the influence of the cooling rate on the interaction between the zirconia core and glass-ceramic veneering. Other aspects to be investigated in DMA studies would be the differentiation and mechanical behaviour of differently doped zirconia.

The study described in chapter 3 was performed in order to verify the subsequent tests with a chewing simulation. It was a first approach for evaluating the influence of laboratory simulation by comparing the clinical survival rate of all-ceramic FPDs with failure rates during in-vitro simulation. A mathematical model based on an exponential decrease of the survival rate was established, which may allow a calculated prognosis of prolonged chewing simulation and in-vitro performance of dental restorations. The significance of this research is limited by the amount of available clinical data, indicating the necessity of evidence, based on
long-term in-vivo investigations. For detailed validation of in-vivo data by in-vitro data, we suggest that clinical trials should be accompanied by in-vitro simulation on identical restorations. Thermal cycling and mechanical loading as structural testing may prove to be a helpful tool to bridge the gap between laboratory tests on standardized specimens (ISO, ASTM) and clinical application. The influence of the geometry or bio-mechanics on the performance of dental restorations can be simulated, but clinical or biological aspects may not be considered up to now.

In the study described in chapter 4, the fracture resistance of zirconia cores has been compared with various veneering ceramics. The results on zirconia FPDs, which were veneered with different ceramic variations in the layering technique, showed that the adaptation of the thermal expansion coefficient and firing temperature of the veneering ceramic helps to avoid interfacial chipping. Higher firing temperatures (>830°C) and thermal expansion between 9.2-10.5 μm/mK should be preferred for the investigated type of zirconia. Further research may focus on thin ceramic layers, which promote the bonding between the zirconia and glass-ceramic veneering. These coatings should be applied in layer- or press techniques at higher baking temperatures and may allow for a better adaptation or wetting of the zirconia core. It should be noted that baking the veneering at a temperature below the required firing temperature carries special risks for the quality of the veneering. In most cases, the veneering and core combination, which is provided as a system by the manufacturer, is recommended, but the application of alternative veneering glass-ceramics from different manufacturers proved to have good results as well.

The results of the study described in chapter 5 show that FPDs that were veneered in layering or press techniques showed small differences in fracture resistance. Variations of press techniques such as press-on or press-over, as well as combinations of press and layering techniques (cut-back-technique) achieved good to sufficient performance during thermal cycling and mechanical loading (TCML) as well as good fracture results after TCML. A modified framework design, which supports the occlusal veneering ceramic, improved the fracture resistance of FPDs, but also showed a higher deviation of the results. Further investigations in this field should be performed, with the goal of finding an optimal zirconia core design. Additional development concerning the strength of the veneering glass-ceramic or innovative types of ceramic for the veneering of zirconia are required. Even alternative veneering with a conventional laboratory composite resulted in fracture values that were in the range of those of glass-ceramic veneering. Composite veneering may be a helpful tool to preserve antagonists, which are at risk and may also enhance the possibility of repairing damaged veneering. Zirconia surface pre-treatment using selective infiltration etching or a phosphoric acid acrylate contributed to the good results.
Chapter 6 deals with the influence of the core ceramic on the performance of the restoration. The study revealed no significant different fracture resistances for three different zirconia FPD systems, including two systems which were manufactured in a “white” configuration or one industrially fabricated “hipped” zirconia. There were no significant differences when the FPDs were conventionally cemented, but adhesive bonding provided an approximately 60-90% lower fracture force compared to conventional cementation. These results may lead to questioning the bonding between zirconia and cement (chapter 8) and the inhibition of the light activated adhesive systems in combination with a non-translucent zirconia framework. The investigation of the marginal adaptation with scanning electron microscopy revealed that 85%-95% of the margins between cement-tooth and cement-crown interfaces had no interruptions or discontinuities and were thus qualified as “good”. The results indicated that under normal conditions, the type of cement had only a limited influence on fracture resistance and the marginal adaptation of zirconia FPDs. These results were confirmed in chapter 7, where the fracture resistance and fracture performance of various ceramic and alloy crowns are compared. This investigation reveals differences in the fracture resistances between the different prosthetic materials, but for the high fracture resistance of the tested zirconia systems, no strength limitations should be expected. There were no significant differences in the fracture resistance between adhesively or conventionally cemented crowns, and therefore, from the clinical point of view, no adhesive bonding should be required for the tested systems, in contrast to glass-ceramic systems. This would therefore allow for easier clinical application, even under moist or sub-gingival conditions. The high strength of the cores was underlined by a fracture pattern, which, in most cases was a chipping of the veneering ceramic and, only in isolated cases, was a fracture of the ceramic core itself. Fractographic analysis revealed that the fracture origin was located on the occlusal surface and caused by superficial wear or disruption in the region of the contact points. Follow-up investigations on clinical failures in this context would help to clarify the type of in-vivo failures in order to increase survival rates.

In chapter 6 there was a hint that adhesive bonding is restricted in combination with zirconia ceramics. Therefore, the study in chapter 8 was performed to investigate the bonding between zirconia and different cements, emphasizing the idea of an easy-to-perform chair-side application of self-adhesive systems. The results indicate that the systems with additional procedure steps are not superior to the simple self-adhesive methods. Three of four tested self-adhesive bonding concepts bonded successfully to zirconia, even after long term storage. The necessity to perform bonding tests after storage longer than 90 days became obvious. It may be assumed that the bonding between zirconia and resin cement is based on cement components such as phosphoric acid acrylate derivatives. The results of chapter 5, where a
zirconia pre-treatment for composite veneering showed good results, underlines this assumption. For providing an etchable surface, a thin glass-ceramic surface layer on the inner side of the zirconia core may be investigated in further studies.

If in the clinical situation zirconia is accidentally exposed to chipping, marginal polishing, or occlusal adjustment, or if it is exposed deliberately by omitting veneering in the connector area, questions regarding the effects of the interaction between zirconia and the oral environment arise. The stability of zirconia under moist conditions is described in chapter 1. However, an accumulation of bacteria may result in increasing plaque formation, causing gingival inflammation and secondary caries. In chapter 9, few significant differences in bacterial adhesion were determined between the different zirconia ceramics. Only individual subject differences were found between glass-ceramics and zirconia. No influence of the substratum surface roughness and hydrophobicity could be determined when the ceramics were polished. Thus, exposed zirconia should not be considered clinically restrictive in terms of bacterial adhesion risks. Investigations should be performed on the consequences of long term and direct zirconia contact with the gingiva.

Summarizing the results, this study supports the assumption that the veneering has a strong influence on the survival rate of zirconia restorations. The chewing simulation showed high survival rates and good clinical behaviour of the zirconia core but also underlined the necessity of an occlusal supporting zirconia core design. This automatically results in an explicit requirement of a constant thickness of the veneering. To achieve good clinical results, further optimization of the veneering ceramic in terms of firing temperature and thermal expansion coefficient is desirable. It is supposed that investigations on the stress distribution between core and the veneering, for example, due to the uncontrolled cooling after veneering, may provide some further information to avoid chipping. Improvements should be achieved by increasing the firing temperatures or strengthening the veneering ceramic. Alternative zirconia manufacturing (e.g. 3D-ceramic plotting) may allow for formation of a zirconia occlusal shape and thus omission of the glass-ceramic. For aesthetic aspects, the application is indeed restricted to posterior areas until a translucent zirconia will be available.

Besides these material aspects, education and training of dentists and technicians may help to improve the survival rates of zirconia restorations. It has to be emphasized that copying porcelain-fused-to-metal techniques is insufficient to fabricate optimized zirconia based all-ceramic restorations. Tooth preparation and fabrication of the restorations must be adapted and application guidelines must be adhered to in order to ensure the quality of zirconia restorations and utilize the high potential of zirconia ceramics.