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Design parameters for all-ceramic dental crowns

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CHAPTER I

Introduction

1.1 General introduction

Less than 3 % of the early hominid Homo Rubustus, who lived between from 1.8 to 1.5 million years ago, had caries [1].

Most likely, changing food habits caused that later hominids developed more caries [2, 3] and modern humans became in need of prosthetic reconstructions. In the Louvre in Paris a dental construction is exposed, which dates from 400-300 years before Christ attributed to the Phoenicians, which may be considered as the oldest known fixed partial denture. The construction consists of four incisive elements (root portion removed) fixed with gold wire to the adjacent elements. Despite the increased effort to prevent dental decay, today many patients are in need of prosthetic reconstructions and present crown and bridgework has to meet high periodontal, functional, and aesthetical standards. The aesthetical aspect in dentistry is becoming more and more important with the improving wealth in the western world and there is high pressure on the dental profession to fulfill the demand for long lasting naturally looking restorations.

The recent discussions concerning the biocompatibility of materials used in restorative dentistry have reinforced the search for alternative restorative materials. The aesthetical properties, the inertness, low thermal conductivity, and low sensitivity for bacterial affixture and plaque accumulation, provided it shows a smooth surface [4], make porcelain a very attractive replacement material for the natural tooth material.

Already in 1886 C.H. Land introduced the porcelain jacket-crown to dentistry. With his technique all-ceramic crowns could be made providing high esthetic quality. However, frequently the dentist had to face the consequences of the brittleness of the ceramic leading to fracture. The introduction of the lost wax technique by W.H. Taggert made first the production of metal crowns possible and later the development of porcelain-fused-to-metal crowns. The porcelain-fused-to-metal crowns were stronger than all-ceramic crowns but still the poor match between framework alloys and veneering porcelain of the thermal expansion of these metal-ceramic crowns often led to failures and fractures. Mixing controlled amounts of high-expansion leucite ($KAlSi_2O_6$) with feldspar glass solved this problem [5]. This invention led to considerable improvement in the reliability of metal-ceramic crowns. The higher strength made these crowns very popular, resulting in a decreasing use of all-ceramic restorations. Nevertheless, the metal substructure of porcelain-fused-to-metal restorations influences the esthetic properties of the restoration negatively. The production of restorations with high esthetic qualities became more an art than that it was based on a predictable and reproducible process. For that reason much effort has been made to improve the strength of ceramic materials to enable a higher frequency of the use of all ceramic application, resulting in stronger ceramics, especially stronger core materials for layered all-ceramic crowns.
Due to the esthetic qualities of all-ceramic layered crowns, which come close to the natural tooth [6, 7], many patients prefer these crowns nowadays. The aesthetic qualities of the natural tooth are influenced by its structure [8]. Dentin is more opaque than enamel and absorbs, and reflects light. Enamel is a crystalline layer over the dentin and is composed of tiny prisms or rods cemented together by an organic substance. The indices of refraction of the rods and the cementing substance are different, as a result, a light ray is scattered by reflection and refraction. As the light ray strikes the tooth surface, part of it is reflected and scattered, while the remainder penetrates the enamel and is either absorbed or reflected and scattered within the enamel. This produces a translucent effect and a sense of depth when the scattered light reaches the eye. To approximate the natural tooth as much as possible, layered all-ceramic crowns are applied. These crowns consist of a core, made with production techniques and materials, which provide the required strength, veneered with a layer or layers of veneering porcelain providing together with the core the aesthetical aspect.

Still all-ceramic restorations are prone to spontaneous fracture, mainly when placed in the posterior region, although the most important factor for the longevity of restorations is a good seal since analyses of failures of fixed restorations have shown caries to be the most frequent cause of failure [9]. Various factors attribute to these phenomena, where the most important ones may be the materials used and shape of the restoration and the cement layer. Different attacks threaten the restoration; thermal, chemical, mechanical loads. In order to make long-lasting restorations it is advisable to have specific design rules for the production of all-ceramic crowns.

For manually produced restorations, design weaknesses can hardly be predicted as the design of the all-ceramic restorations with respect to the ceramic layer design as well as the outer shape is an operator dependent property. However, for computer designed and manufactured restorations (CAD-CAM: Computer Aided Design-Computer Aided Manufacturing) these parameters as well as those of the preparation are digitally available, making stress analysis and failure prediction possible. Finite Element Analysis might be a proper tool to perform such analysis.

1.2 The material properties

Dental ceramics are a compound of metals (such as aluminum, calcium, lithium, magnesium, potassium, sodium, tin, titanium, and zirconium) and nonmetals (such as silicon, boron, fluorine, and oxygen) that may be used as a single structural component used in the fabrication of dental restorations [8]. The production of ceramic restorations can be described as a complex sequence of high temperature reactions occurring above the softening point of the ceramic and leading to partial melting of the glassy matrix, with coalescence of the metal-oxide particles.

The first dental ceramics developed for dental restorations consisted of feldspathic ($KAlSi_3O_8$) or aluminous (Al_2O_3) porcelain, which was baked on a thin platinum foil. These restorations can be considered the ancestors of all-ceramic crowns. The introduction by J.F. McLean in 1965 of a ceramic core out of sintered aluminum oxide made the production of reliable all-ceramic crowns possible [10]. New materials and production techniques such as heat-pressed and slip-cast ceramics were developed to produce stronger all-ceramic cores [11].

With the pressing technique dry material is pressed and sintered after pressing. Alumina-, magnesia-, and zirconia-based porcelains are used with this technique (for example Procera®, and Cicero®). The process of heat-pressed ceramics relies on the application of external pressure at elevated temperatures to obtain sintering of the ceramic body (for example Empress®). Casted ceramics (for example Dicor®) are ceramics that are heated and casted into a mold. Slip casting involves the condensation of an aqueous porcelain slip on a refractory die, fired on the refractory and the fired porous core is later glass infiltrated (for example In-Ceram®). For layered all-ceramic crowns these core materials are veneered with veneering porcelain layers. The mechanical properties of ceramics are determined by the shape, sharpness, size and depth of surface flaws as well as by internal flaws [12]. The failure of ceramics being a brittle material is attributed to the propagation of a large system of densely distributed cracks, rather than to a single precisely defined fracture [13]. Loading of the restoration will cause wear [14], reshaping the surface, which will introduce surface flaws. These flaws influence the mechanical properties.

For the luting cement used to retain the restoration, and to fill and seal the gap between tooth and restoration materials, cements that show good adhesive properties are becoming increasing popular[15]. A variety of cements have been used in dentistry through the years to retain restorations in a fixed position within the mouth [16]. The required properties for dental cements equal those of other restorative materials. As a result, the general use of cements for restorations exposed to the oral environment is quite limited. Zinc phosphate is the oldest of the cements and thus is the one that has the longest track record. Actually a number of materials are available for cementation purposes. These include zinc phosphate, zinc silicophosphate, zinc polycarboxylate, glass ionomer, zinc oxide-eugenol and resin-based cements. Resin-based cements have become the luting cement of choice recently. Resin-based cements are virtually insoluble [17], and their fracture toughness is higher than that of other cements. They bond to dentin by means of a dentin bonding agent, and can form a strong attachment to enamel as well as to ceramics via the acid-etch technique. From a biological standpoint, the cements may irritate to the pulp [18]. Thus pulp protection via a calcium hydroxide or glass ionomer liner [19] is important when one is cementing an indirect restoration that involves bonding to dentin with insufficient dentin thickness.

1.3 CAD-CAM

Cicero® is one of the more modern CAD-CAM systems [20] that consists of optically digitizing the preparation, its immediate surroundings, and the antagonists with a laser surface scanner; indirect by scanning of a gypsum model. Some other systems use scanning directly in the mouth. The digitized information is read into a computer aided design program to design the crown with the different layers (CAD). The crown is designed by selecting the proper tooth from a library, modeling the crown on the screen to fit in with the remaining dentition, and making final adjustments to the proximal contacts with the computer. Like in most modern programs the occlusal surface is formed by the program itself where the functional relationships are ensured for both dynamic and static conditions. After the interior and exterior tooth surfaces have been designed, several interface surfaces between cement and ceramic core and between different veneering porcelain layers are defined. The negative of the inside surface of the crown is accurately milled on refractory material. On this material, core material is pressed and pre-sintered. Subsequently, the outer surface of the core is brought into the desired shape by milling from the pre-sintered material in a computer driven milling machine into the desired shape using the CAD information (CAM) and subsequently sintered. Hereafter, the veneering porcelain layer or layers are applied on the sintered core by pressing on veneering porcelains, which are sintered and subsequently milled in the designed shape.

1.4 Finite Element Analysis

Finite Element Analysis (FEA) was originally developed in the aircraft industry and has since then been widespread in engineering in the industry, going from accounts of the thermal stresses in a reactor vessel to civil engineering. It was also concluded for dentistry that finite element analysis proved to give reliable information concerning stress distribution in a tooth [21]. The solution method of finite element analysis consists of dividing the geometry into a finite number of elements with relatively easy to describe mechanical properties, which can be wedges, tetrahedrons or other solid elements. The classical theories of mechanics together with the approximation of dividing the geometry into a finite number of elements give the possibility to calculate mathematically the stresses in a geometry resulting from loads on it. The impressive development of computing capacity even with standard personal computers makes it nowadays possible to calculate accurately stress development in complex geometries like a tooth preparation with crown.

The use of multi layer ceramics in combination with an ultra thin adhesive layer, whose mechanical behavior is so largely associated with shrinkage problems, imply that 3D finite element analysis is practically the only way to obtain a meaningful image of al processes, which simultaneously take place.

1.5 Scope and contents of this thesis

The aim of the present research project was to evaluate by finite element analysis the influence of design parameters of the preparation and the cement layer on the stress distribution in CAD-CAM produced all-ceramic crowns and their cement layer. Since certain material properties were not available in literature some material properties had to be studied.

Chapter 2 Chapter 2 deals with mechanical properties of ceramics. The mechanical properties are determined by the shape, sharpness, size and depth of surface flaws as well as by internal flaws [12, 22]. In order to adjust occlusion, the functional surfaces of porcelain restorations are often ground, mechanical machining is even an essential part of the CAD-CAM process, and loading of the restoration will cause wear, reshaping the surface, which will introduce surface flaws. For these reasons the influence of the surface roughness on porcelain strength was studied.

Chapter 3 The bond of adhesive luting cements to the tooth tissues and restorative materials is expected to hinder their transverse contraction during setting [23, 24] for the layer thickness applied in dental restorations. The hindering of the transverse deformation may influence the relation between stress and strain, the stiffness, in the direction perpendicular to the substrate surface. In Chapter 3 the relation between cement layers with different ratio between bonded and free surface (C-factor) [25] and the stiffness of these layers *i.e.* an apparent increase of the Young's modulus of the dental luting cement was investigated.

Chapter 4 The knowledge of the polymerization shrinkage stress development, distribution and height is of main importance for a reliable risk assessment of the durability of dental indirect restorations. To reveal this process is hard to perform, as the setting of resin composites is a complex time depending process, throughout which material properties undergo a dramatic change in a relatively short period. Moreover, the complex geometries found clinically are rather difficult to imitate in a laboratory setup.

As a consequence the stress found in simplified laboratory test setups may not fully mimic the complex clinical cases.

In chapter 4 a model for the visualization of the setting stresses caused by the time dependent dynamic setting behavior of resin composite luting materials in cement gaps with uniform thickness mimicked by a time independent static FEA model is described.

Chapter 5 The obtained material properties were used in a FEA evaluation of the crowns of 3 patients. This evaluation resulted in specific design rules, for full ceramic crowns in the posterior region, which have to be followed and which are presented in chapter 5.

The chapters 2-5 in this thesis can be read independently, as they have been written in a form suited for publication in international scientific journals.

1.6 References

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