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BIOMECHANICAL ANALYSIS OF INDIVIDUAL ALL-CERAMIC ABUTMENTS USED IN DENTAL IMPLANTOLOGY

The paper presents the results of finite element analysis and experimental testing under simulated physiological loading conditions on issues shaping the functional properties of individual all-ceramic abutments manufactured by CAD/CAM technology. The conducted research have cognitive significance showing the all-ceramic abutment behavior, as a key element of the implantological system, under the action of cyclic load. The aim of this study was evaluation the fatigue behavior of yttria-stabilized zirconia abutment submitted to cyclic stresses, conducted in accordance with EN ISO 14801 applies to dynamic fatigue tests of endosseous dental implants.

Keywords: Dental implant, Abutment, Zirconia ceramics, Cyclic fatigue

1. Introduction

Dental implants, as a result of their excellent success rates and advantages over fixed or removable methods, have for many clinicians become the optimal treatment for replacing missing teeth. Today, it is one of the most exciting and rapidly developing aspects of dental practice. Some restorative applications of dental implants, usually made from titanium or titanium alloy, include supporting crowns, bridges, or dental prostheses [1]. Prosthetic works upon implant may replace from a single tooth to an entire arcade – and is dominated by screw fixing – Fig. 1.

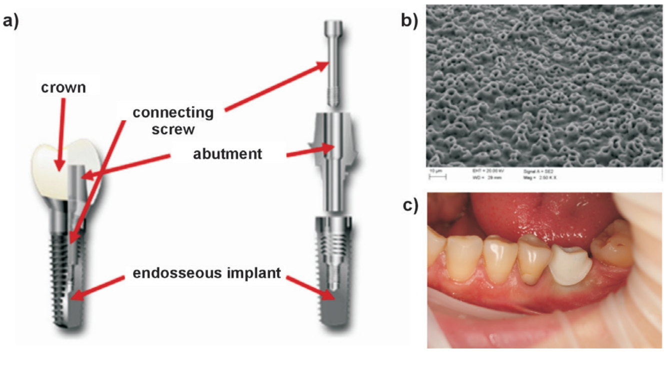

Fig.1 Implantological system: a) components, b) SEM micrograph of the implant's surface, c) individual ceramic abutment

Contemporary clinical and laboratory management in the field of manufacturing of fixed prostheses based on dental implants, as well as patient expectations, concentrate on obtaining more and better aesthetic effects. The development of dental materials science, and especially the part related to the technique of scanning and milling object structure of ceramic materials leads to successive elimination of metal alloys in dental prosthetics. Considerable interest and usefulness has undoubtedly zirconia [2,3]. The main reason for such interest was the development of computer-aided design / computer-aided manufacturing techniques technology (CAD/CAM) in the late twentieth century. The increasing demands of patients and desire as faithfully as possible imitating the nature of prosthetic restorations, causes an increase in the number of augmentation and transplantation procedures and the increasing use of patient-specific (custom-made) abutments, crowns and bridges made of zirconium oxide in the CAD/CAM technology [4÷7]. It means that there is a growing interest in the machinability of medical ceramics – creating new possibilities, relating to both the content, and precision processing. Because of its high strength and comparatively much higher fracture toughness, sintered zirconium-oxide can be used in frameworks for all-ceramic posterior crowns and fixed partial dentures [8], implant and abutments [9], root dowel pins and brackets for orthodontic treatment [10]. The indications for the use of zirconia oxide in prosthodontics include esthetically challenging areas, such as the maxillary anterior region, where thin gingival tissue and a high smile line are present, as well its mechanical properties that are attractive for restorative dentistry, which include its chemical and dimensional stability, high flexural strength and fracture toughness. The yttria stabilized zirconia (Y-TZP) ceramic has twice the flexural strength toughness of alumina ceramic (900-1400 MPa), fracture toughness of up to 10 MPa/m$^{0.5}$, and a modulus of elasticity value of 210 GPa. The main reason of superior resistance of zirconia lies in the stabilizing effect of yttria [11]. One of the advantage of the performance of custom-made abutments is the possibility of obtaining

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a similar geometry to the shape of the grinded tooth and make it easier to shape the emergence profile. At the same time not to be underestimated is the fact that the material is similar in color to the tooth – which is important as far as esthetic is concerned. Compared to metal abutments, zirconia abutments offered optically favorable characteristics, low corrosion potential, high biocompatibility, and the low thermal conductivity. An additional advantages seems to be a radiological opacity that allows for clinical monitoring and reduced susceptibility to accumulation of plaque, compared with titanium abutments. On the other hand, restoration made out of such material were weaker when compared to metal-ceramic restorations [12].

There are several factors that may affect the fatigue and fracture behavior of materials used in implantological system. The very important to the strength of the used system is construction of the customizable ceramic abutment, and particularly its anti-rotational element that should be sufficiently thick-walled to prevent them from breaking. The disadvantage of these supplements may be the need to respect the appropriate thickness abutment due to the characteristics of the material [13]. Also height of abutment is fundamental to obtain ZrO_2 frameworks with correct shape and dimension in order to ensure mechanical resistance restoration [14]. Garine [15] believes that freedom of rotation for all-ceramic abutments is much greater than titanium connectors, which can increase the risk of damage. By increasing the tension on the connecting screw may occur complications associated with the loosening or failure [16]. According Khraisat et al. [17] mismatch on the surface of the implant - the abutment (unstable screw joints) may lead to mechanical complications under continuous cyclic loading, which may include: excessive rotation of the abutment with the possible destruction or fracture of the implant nest, loosening or destruction of the abutment's connecting screw. Screw loosening is the most common mechanical complication of implant therapy [9].

2. Materials and methods

The yttria-stabilized zirconia abutments, used in the study, were prepared by utilizing CAD/CAM manufacturing techniques. Their geometry was mapped on the basis of the shape of titanium-ceramic connectors designed for commercially Nobel Biocare implant with a diameter of 4.3 mm. This kind of implant mimics the shape of the natural tooth root.

Before the start of the study, microscopic observations were made of abutments and connecting screws surface condition. All mentioned elements were imaged with a scanning electron microscope (SEM; SUPRA 35, Zeiss) in a secondary electron emission mode at the beginning and end of the experimental dynamic fatigue testing at magnifications of 60x to 700x.

Numerical analysis and in vitro study was performed in accordance with [18] applies to dynamic fatigue tests of endosseous dental implants. It takes into account a description of the operating parameters of the implant under dynamic loads, which are defined as the most unfavorable.

2.1. Numerical analysis of dynamic fatigue test

The fatigue calculations were performed with the finite element method. The first step of numerical analysis was to create of geometric models of all the components of the implantological system: the implant, connecting screw and zirconia abutment. The implant parts were modeled in accordance with the geometric designs (on the basis of technical documentation) and scanning electron microscopy observation. In order to limit the total number of elements in the finite element model the implant geometry was simplified to a cylinder with a conical apex.

Models were designed in Autodesk Inventor 11, and simulation studies were performed in ANSYS Workbench – Fig 2 a÷c.

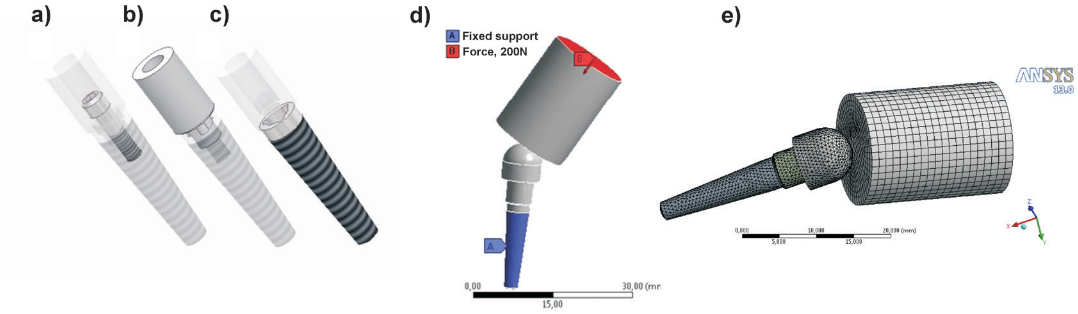

Fig. 2 Geometrical models of: a), b) all-ceramic abutment with a connection screw, c) implant, d) scheme of the experiment, e) meshed model

	Steps	Time [s]	Force [N]
1	1	0	0
2	1	1	200
3	N/A	3	20
4	N/A	4	200

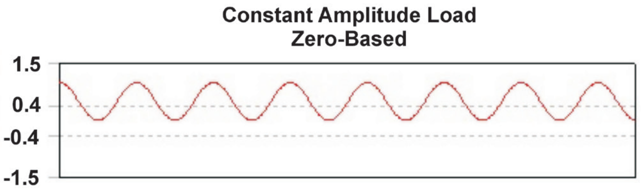

Fig. 3 Model of the fatigue load in the form of a sinusoidal function

TABLE 1

Material data defined for the components of the implantological system

Component	Material	Young's modulus [GPa]	Poisson ratio	Density [g/cm^3]	Tensile strength [MPa]	Yield strength [MPa]
Implant	Ti Grade IV	103	0.41	4.51	552	483
Connecting screw	TI6AL4V ELI	120	0.33	4.43	970	930
Abutment	Y-TZP	210	0.31	6.00	Flexural strength 1400	

Materials data – necessary to simulate the fatigue – were taken from the literature [19÷25] and are presented in Table 1. Fatigue loading model in the form of a sinusoidal function, mapping the real load on the implant is shown in Fig 3.

The engagement point and the direction of load relative to the axis of the implant (force: 200 N) reflects Fig 2d. The area corresponding to the implant intraosseous contact with the bone tissue has been marked as permanently fixed (Fixed Support), which simulates the conditions for proper bone healing. The scope of the analysis included also the determination of the maximum displacement in implant-abutment complex and the maximum equivalent stress in all of the components.

2.2. Experimental dynamic fatigue test

Fatigue is one of the major factors that can predict the success of the restorations. Additionally, the evaluation of the fatigue behavior of components of the implantological system can make it possible to evaluate the type of failure of system and identify its weakest element – designed to correspond as closely as possible to physiological conditions.

In study, the effect of fatigue testing on the properties of zirconia abutment and connecting screw was evaluated. An endosseous internal type dental implant (Nobel Biocare) includes ceramic abutment was clamped such that its axis makes 30° ± 2° angle with the loading direction of the testing machine (MTS Criterion). The abutment was tightened with standard screws supplied by manufacturer with a dental implant torque wrench (25 Ncm). The implant/abutment screw/abutment combination is hereafter referred to as the assembly – Fig. 4. The loading force, F, of the testing machine was applied through a deformation-resistant loading member with a hemispherical contact surface for load transfer, placed over the free end of the ceramic abutment. The loading centre was on the central longitudinal axis of the implant.

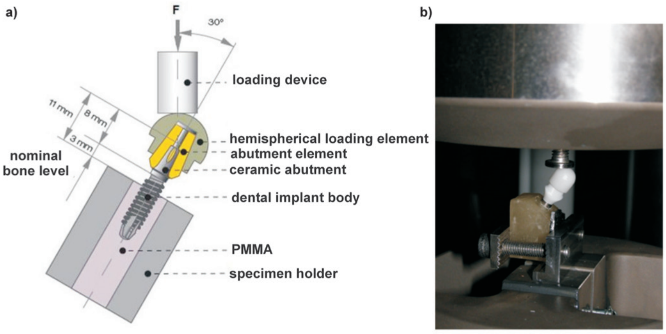

Fig. 4 Abutment assembly fixed within implant: a) schematic of test set-up, b) test stand

The implant was embedded in resin, with a Young's modulus similar to the bone tissue, at a distance 3.0 mm ± 0.5 mm apically from the nominal bone to provide a representative case with respect to bone loss. Fatigue testing was carried out with a unidirectional load. The load vary sinusoidally between a nominal peak value (200 N) and 10 % of this value (20 N). The loading frequency was 10 Hz. The testing device delivered sine curved cyclic loading for 5 x 106 cycles (NF). According to [26] the average daily number of mastication is about 2,700 and so 5000000 cycles corresponds approximately fully functional use of the implant within to around nine years.

3. Results

3.1. Numerical analysis of dynamic fatigue test

The results of fatigue analysis are presented by plotting the fatigue resistance of structures and maps relating to: the lifetime of the structure, the stresses and displacements distribution. Obtained values demonstrate excellent fatigue properties of the materials constituting the components of the implantological system. Infinite durability of construction confirms the fatigue life graph, as shown in Fig 5, obtained for given boundary conditions. As a result of the calculations were also obtained stress distribution for implant system (Fig. 6,7), resulting from a given cyclic loading. Stress values vary for the different cases, reaching maximum values within a data element from 75.227 MPa in the case of connecting screw to 242.7 MPa for zirconia abutment.

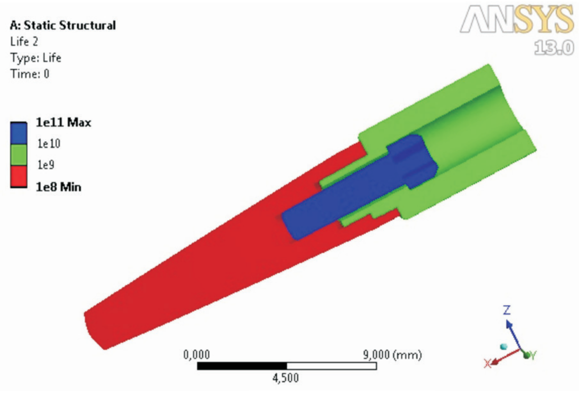

Fig. 5 Lifetime of construction – the cross-sectional view

Stress values observed on the maps distribution should not influence the formation of typical mechanical damage.

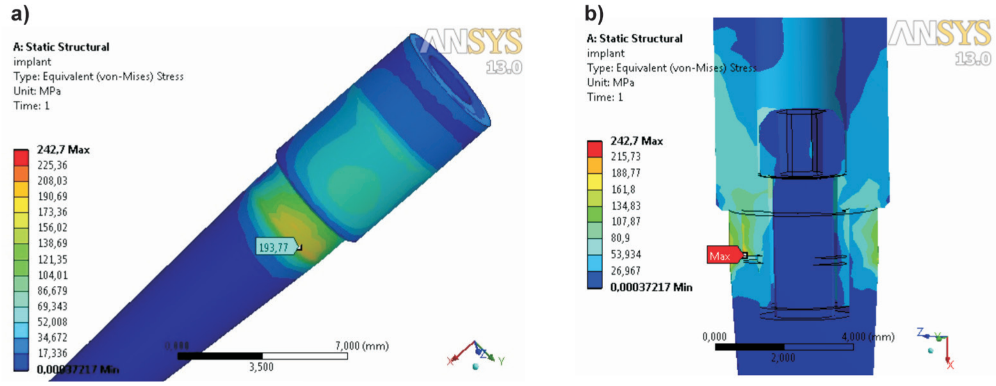

Fig. 6 a) Map stresses occurring in the components of the implant caused by cyclic loading, b) stress occurring at the place of connection elements + cross-sectional view

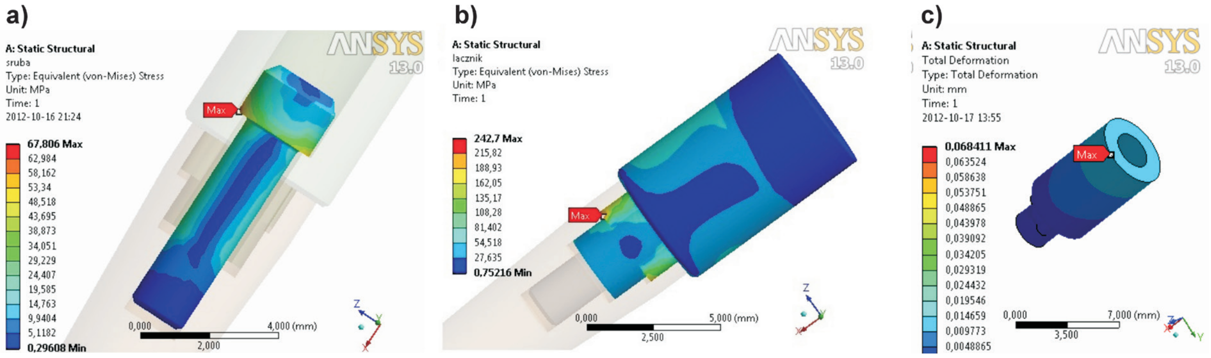

Fig. 7 The stress distribution in the: a) connecting screw, b) abutment, c) displacements occurring in the abutment

Given the cyclical nature of the load implant specific areas of stress concentration could be the potential risk areas of the fatigue damage. However, due to the complexity of the physiological characteristics of the variation of the load of the implant and to simplify the geometry of the model, it is impossible by a simple calculation to estimate the degree of risk.

From the point of view of the mechanical work of the implant, it is important that the stresses present in the ceramic abutment, as well as the connecting screw and the implant do not reach the flexural strength and yield strength respectively.

3.2. Experimental dynamic fatigue test

Fatigue testing was carried out at cyclically varying loads of predetermined amplitude, and the number of load cycles until failure occurs was recorded. Failure is defined as material yielding, permanent deformation, loosening of the implant assembly or fracture of any component of the examined implantological system. The results of testing are summarized by representing the number of load cycles endured by examined implantological system with ceramic abutment (on a logarithmic scale) and the corresponding peak load (on a linear scale) – Fig 8.

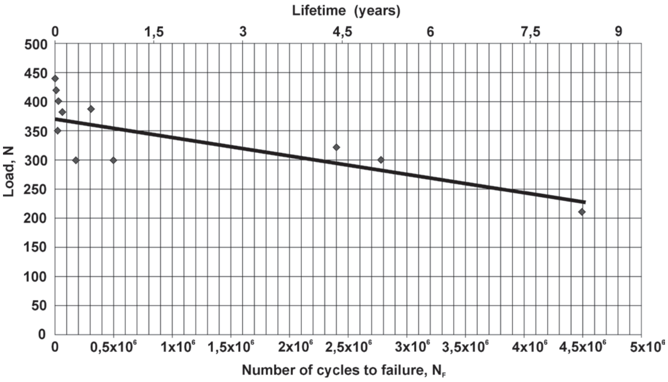

Fig. 8 The load-cycle diagram the fatigue limit of the implantological system with the zirconia abutment

The study did not confirm a fully functional use of the system in the assumed normatively intervals. Fracture of the abutment was accompanied by an audible pop. The ceramic abutment and connecting screw was examined after test to check what kind of deformation had occurred. Fractographic images of the fractured surfaces of abutments failed from fatigue testing showed the numerous cracks and material losses – Fig 9. It was also observed loosening of the connecting screw, caused by destruction of the scrolls – Fig 10. Based on these results one can specimens that survived to the fatigue limit of 500,000 cycles.

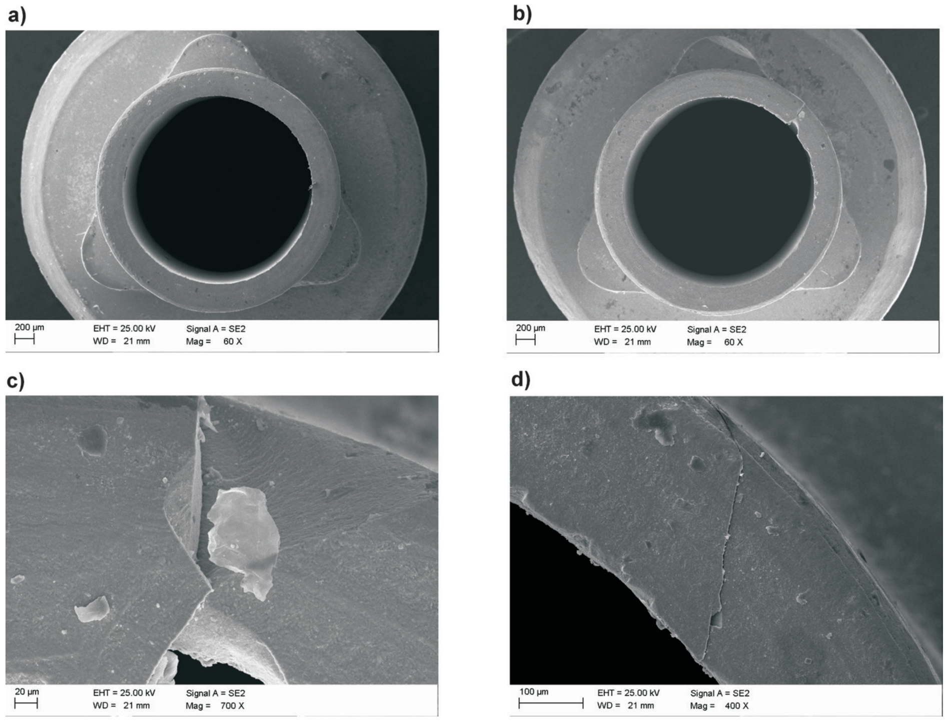

Fig. 9 SEM images of the ceramic abutments surfaces: a) before, b) ÷ d) after dynamic fatigue test

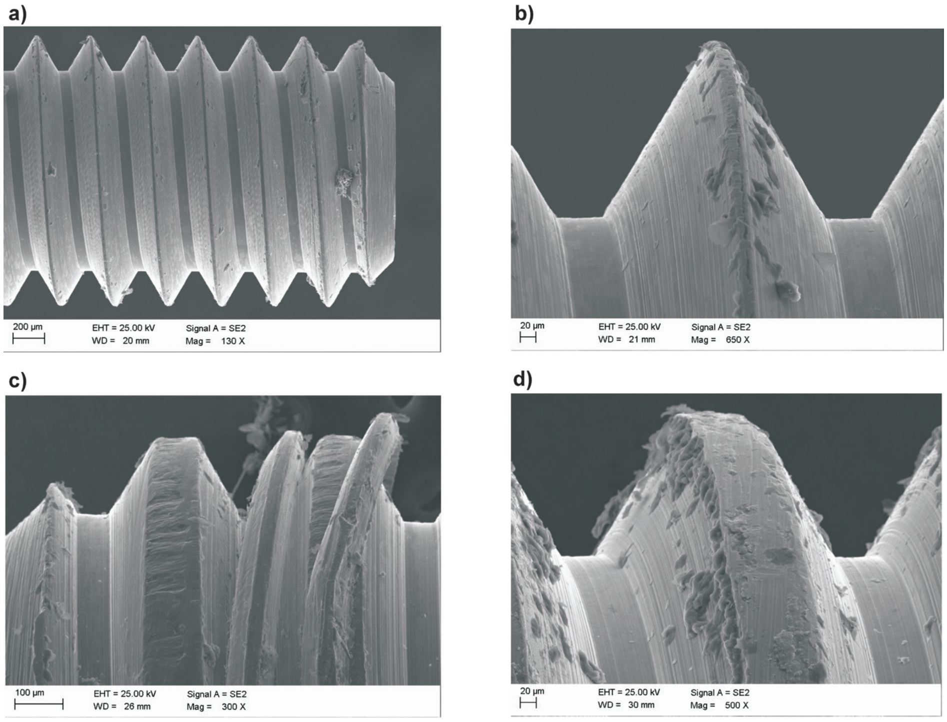

Fig. 10 SEM images of the connecting screw threads surface: a), b) before, c), d) after dynamic fatigue test (visible destruction of the scrolls)

4. Conclusions

The work presents results of biomechanical analysis of the multi-part endosseous dental implant system. The analyses were carried out with the use of finite element method and experimental testing under physiological loading conditions – in vitro. Experimental analysis of dynamic fatigue has verified the results obtained in numerical analysis.

The study showed:

- the destruction of the ceramic abutment and connecting screw, thereby causing a loss of stability of the implantological system; the force used in this study (200 N) was lower than the biting force in a molar region, which is quoted as ranging from 400-800 N [27];
- the repetitive loads generated during chewing cycles leaded to the fatigue of the materials. The dental restoration is usually exposed to the cyclic loading;

therefore, fatigue is one of the major factors that can predict the success of the restorations;

- the applied methodology of fatigue FEM calculation, excludes the impact of pre-loading by tightening the screws, the effects of bone structure remodeling (changes in stiffness) and bone loss, in which the implant has been placed. It was assumed an ideal conditions of osseointegration and omitted issues related to tightening the clamping screw, assuming the place of a threaded connection as correct combination of flat surfaces.

Variable loads in screw connection leads to a complex state of stress, which results in the number of lesions characteristic for material fatigue. Applied cyclic load was most likely cause of the friction between the connecting screw and the implant. It was most probably cause of disappearance of tightening torque resulting in damage of the threaded connection.

Three-dimensional techniques and axisymmetric implant-shapes modeling may provide a ready-made tools in future work on optimizing existing implant systems. Used in research advanced FEM calculation tools would help to minimize the occurrence of fatigue damage in the oral cavity under physiological loading conditions.

Due to the fact that a dental restoration is usually exposed to the aqueous environment; therefore, the fatigue behavior of dental ceramics abutments under water should be designed to correspond as closely as possible to physiological conditions. Fatiguing specimens would be more related to the clinical situation; however, this project would like to focus on fatigue property of the zirconia abutments.

Appearance of the mentioned effects are a clear warning signal and the situation, which would not allow. One should be aware that any fatigue failure may result in serious complications of a medical nature. The nature of the load dental implants, variability of boundary conditions, their complex geometry and mechanical system, causing difficulties in applying analytical methods for the calculation of fatigue. Moreover, a drawback of all-ceramic materials is their susceptibility to fatigue mechanisms that can considerably reduce their strength over time and, therefore, the lifetime of structural load-bearing components. Therefore, a more reliable method seems to be the evaluation of the fatigue behavior of e.g. new shape of a ceramic abutment under simulated physiological load conditions. Since dental restoration are obviously exposed to cyclic loading, the determination of functionality of abutment under such conditions is a primary requisite for the successful application of all-ceramic prostheses in dentistry (its lifetime).

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