BIOMECHANICAL STUDY OF DISK IMPLANTS Part I

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The presented work is focused on the biomechanical study of the dental disk implant. The first part of the study deals with the strain analysis of the affected bone tissue and the dental implant loaded in the coronoapical direction by force 190 N. The study includes three types of implant anchorage, four degrees (stages) of osseointegration and nine degrees describing the quality of the cancellous bone. Two types of the disk implant were researched: single-disk and double-disk implant. Biomechanical study of the implant was focused on a stress-strain analysis of the affected bone tissue. The biggest influence on the stresses in the bone tissue was primarily an implant anchorage. By the application of correlation relationships between Young modulus and the apparent density of the bone tissue – which is measurable in patients – we achieved the variable presented in this study.

Keywords: dental implant, osseointegration, FEM, bone, density

1. Introduction

No one today can do without dental care. Not only for young children but for most adults as well, the white coat represents an increased level of adrenaline and stress. This affects the atmosphere in the waiting rooms of dental offices. By simple analysis of the described phenomenon we can find out that at least two factors play important roles: Fear of a painful medical treatment and consequences of the disease itself. The second factor can (depending on seriousness of the disease) significantly prevail over the first one. Though the teeth diseases are not fatal, the fear of losing a tooth or a part of teeth is great with both young and elderly people and the growing probability that this situation can occur is also stressful. This is mainly caused by the fact that there are not many possibilities of how to replace a lost tooth, a part of the dentition or the whole dentition. The best, most comfortable, most considerate to one's own dentition but also the most expensive solution is to use a dental implant.

Dental implantology is a very broad field; one of the significant factors affecting this field is the age of patients. Currently, the dental implantation is carried out for patients ranging in age from infancy through adults to seniors. At every age, the dental implantation has, despite the fundamental objectives, i.e. the replacement of lost tooth, varying importance and its own specific problems. Age is a significant parameter in terms of reasons for and the frequency of tooth loss and the frequency of dental implantations. The age of man, on the one hand, increases a likelihood of tooth loss; on the other hand it leads to a deterioration of

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Fig.1: Assessment of the bone tissue quality (Misch) [1] and mandibular alveolar ridge resorption (Lekholm a Zarb) [1]



Fig. 2 Mandible – cross section

the quality of the bone tissue and thereby worsen conditions for the successful implantation. Especially in the case of elderly people who often suffer from the loss of part or the whole dentition, alveolar ridge resorption can be encountered (Fig. 1) and also the pathological decrease of the bone tissue [1], where mild form is known as osteopenia and the severe form as osteoporosis [2] (Fig. 2). As far as successful implantation in these cases is concerned, proper attention to the implant selection should be paid. Some doctors recommend the so-called disk implants which are specially developed for such cases. The principle of the disk implants is that a mechanical interaction occurs between the implant and both the cancellous and cortical bone tissue (Fig. 3).

2. Material and methods

The presented work describes a biomechanical study of the mechanical interaction between the implant and the bone tissue in terms of the quality of bone tissue, the osseointegration level, and the character of the implant anchorage. The quality of the bone tissue will taken into account and described in detail in the section dealing with the creation of material model. Basic types, in terms of implementation, are the single-disk and multiple-disk implants. This study includes two implants: single-disk and double-disk (Fig. 5).

Two states are considered in terms of the connection between the implant and the bone. The first state describes the situation in which the connection has not occurred yet and the mechanical interaction has therefore not arisen. The second state describes the situation of the complete implant-bone osseointegration^{*}. The state with a transitional connective-tissue is inadmissible from the medical point of view; therefore it is not taken into account in the study. In this work, the osseointegrational progression in all parts of the implant was modeled gradually in four degrees (see Fig. 3). The parts of the implant, where the osseointegration was not present, are denoted in grey color as opposed to the parts, where the osseointegration occurred and which are denoted in black.

The study also includes three biomechanically possible variants of the anchorage labeled A, B and C (see Fig. 4).

^{*} The basic study of the interaction between implants and the bone tissue made by Branemark in 1952 by using a microscope with rabbits [3]. The most important finding of this study was that the successful implantation occurs where a rigid connection of the bone tissue and the implant arises with no transitional (connective) tissue. Although there are currently other views on this issue, most dental implantologists and workplaces, where the dental implantology is performed, agree with the conclusions of Bramenark's study.



Fig.4: Variants of implant's anchorage

Variant A represents a mechanical interaction between the implant disk and both the inner and outer cortical bone. In the case of variant B, the interaction is only with the outer cortical bone while in the case of variant C the implant disc is smaller than the space between the outer and inner cortical bone. This last variant represents interaction with the cancellous bone only.

3. Solution method

Based on the analysis of shape, material properties of the system components and the character of the system constraints, the finite element method (i.e. numerical calculation method) has been chosen as the effective method for the solution of quantities describing the mechanical interaction between the implant and the bone tissue. For the solution of the given problem by means of FEM, it is necessary to create a computational model which consists of four relatively independent parts: model of geometry, materials, loads, and constraints.

4. Model of geometry and constraints

The problem solved in this work is the mechanical interaction between the disk implant and mandibular bone tissue. The implants affect strain and stress fields only in their close vicinity. The geometry model of the bone is created as a 20 mm-long section of the mandible and, to be more precise, this section represents the first molar region. Mandibular geometry was obtained from the real mandible with the optical scanner ATOS Standard. The cortical bone thickness was modeled on the basis of CT images [4]. Dimensions and shape of the implant are based on the catalogues of companies Ihde [5], AirPerio [6] and Victory [7] – see Fig. 5.

5. Material models

The parts forming the real system are from different materials; the material of the implants is the titanium alloy Ti6Al4V. In terms of the level of the solved problem, the appro-



Fig.5: Geometry model of disk implants

priate and validated model of mechanical properties is a homogenous, isotropic and linearly elastic model, which is explicitly described by two material characteristics: Young's modulus (E) and Poisson's ratio (μ). The bone – i.e. the part of the mandible – is composed of the cortical and cancellous tissue; a description of mechanical properties of the cortical and mainly the cancellous bone tissue is much more complex. The influence of the level of the cortical and particularly the cancellous bone model on the strain and stress in biomechanical systems is still a very difficult problem. The cortical as well as the cancellous bone tissue are therefore modeled by the homogenous, isotropic, and linearly elastic model. This fact is fully respected in the analysis of results. Material characteristics used for the described material models, applied in computational solution, are listed in the following table.

The deterioration of bone tissue quality (see Fig. 1a) is reflected in the value of the Young's modulus of the cancellous bone. Calculations were carried out within the value of the Young's modulus in the range of 20–100 MPa with the increment of 10 MPa.

Material	E [MPa]	μ [–]
Cancellous bone	20 - 100	0.3
Cortical bone [8]	13700	0.3
Titanium alloy [8]	116000	0.34

Tab.1: Mechanical properties

6. Model of loads and constraints

During mastication, the tooth is loaded in a general direction. After a decomposition of the general loading to the coronoapical, buccolingual and mesiodistal directions, the largest component is in the coronoapical direction. Considering the scope of the study, only the greatest component, i.e. in the coronoapical direction, was taken into account. Its value of 190 N was taken from literature [9], [10] and it was applied as a statically equivalent pressure on the upper surface of the implant body.

The model of the bone is constrained in its cross section on the distal side (closer to the temporomandibular joint) by restricting of all displacements of all its points. The implant is bounded with the bone according to the degree of osseointegration (see Fig. 6). In case of complete osseointegration, the constraint between the implant and the bone is rigid. If no osseointegration occurred, the connection between the implant and the bone is realized by the contact-type constraint. The variants of the degrees of osseointegration are shown in Fig. 3.



Fig.6: Boundary conditions

7. Computational – finite element model

To create a computational model for a computational solution by means of the finite element method it is necessary to carry out a discretisation with respect to a computing system, whereby the solution is implemented. In our case, it is the system Ansys 11. The discretisation was carried out by using elements SOLID187 and SOLID186 and for implementing the contact-type constraint CONTA174 and TARGE170. Maximal attention was paid to the discretisation (see Fig. 7). The number of elements and nodes was different in the individual variants. In case of elements the number ranged between 100 and 260 thousand, in case of nodes the number ranged between 400 and 600 thousand. Contact surfaces were bounded with 10 to 30 thousand contact element pairs.



Fig.7: Discretisation

8. Solution

To assess the mechanical interaction of the implant with the bone, 24 computational models were created. These computational models were created for two different types of the implants; for both types three variants of the anchorage and four degrees of the osseointegration were modeled.

Nine calculations taking into account the bone quality by changing of the Young's modulus in the range 20–100 MPa were realized for each computational model.

The solution was implemented on PC with Intel Core 2 Duo 2 GHz processor with 2 GB of RAM memory and 300 GB hard drive.

Since the contact problem is solved and the materials with very different material characteristics (in particular the Young's modulus) are used, it is necessary to choose an appropriate solver. Therefore, the iterative PCG solver and full Newton-Raphson method were used. The accuracy of the PCG solver was set to 1.0×10^{-5} . Due to the character of the problem and the computational model, the solver was set to the large deflection mode. Other parameters were left at the default setting. The duration of the solution varied depending on the extent of nonlinearities from 30 minutes to 14 hours.

9. Presentation and analysis of results

Disk implants are designed especially for mandibles with low quality of the bone tissue which occurs mainly in elderly people. Besides age, other factors can also affect the quality of the bone tissue.

Unlike an implant, which is the technical work created by a man, and whose mechanical properties can be affected by e.g. design, material and appropriate application, we have substantially fewer means to improve the mechanical properties of the bone tissue. When considering availability as well as effects on the organism and cost, it can be stated that there are hardly any. Therefore, the analysis of mechanical quantities describing the state of the bone tissues of the loaded segment is important. In respect to the scope of the study (216 calculations) the results analysis of the first part of the study is devoted only to the bone tissue. Analyzed quantities are the coronoapical displacement of the implant u_z and the strain intensity in the cancellous bone :

- 1) The implant displacement u_z because it is a measurable quantity. Since this is a very difficult experiment, the number of references in the literature is very limited. [11] describes the measurement of the tooth displacement u_z . The tooth movements ranged due to the soft periodontium from 0.05 to 0.1 mm. The results of a similar study for the mandible with an applied screw implant (diameter 4.1 mm, length 11 mm) are presented in [12]. In this case the value u_z ranged from 0.005 to 0.06 mm.
- 2) The strain intensity* in the cancellous bone because there are references in the literature which (based on the strain intensity in bone tissue) define the state of the physiological remodeling, the mild overload state and the pathologic overload state [13], [14], [15].

Firstly, the implant displacement u_z depending on the Young's modulus of the cancellous bone and the degree of the osseointegration will be analyzed. Displacements, depending on the mentioned quantities, are depicted in the following graph in Fig. 8.

The graph shows that the displacement depends significantly on the degree of the osseointegration. For all degrees except the complete osseointegration, with decreasing Young's modulus of the cancellous bone the displacement u_z progressively increases. In case of the complete osseointegration, the displacement u_z is almost independent of the bone quality. The influence of the second disk on the displacement u_z depends significantly on the degree of the osseointegration as well. In case of the complete osseointegration as well as no osseointegration of the upper part of the implant post with the cortical bone, the displacement u_z is almost the same for both the single-disk and the double-disk implant. For other degrees of the osseointegration, with the decreasing osseointegrated area the progressive in-

^{*} The quantity labeled in Ansys as 'strain intensity' is in this computational system defined by formula $\varepsilon_{\text{int}} = \varepsilon_1 - \varepsilon_3$, where ε_1 and ε_3 are the 1st and 3rd principal strains [16].



Fig.8: Influence of the post-displacement on the Young's modulus and degree of osseointegraion – variant A

crease of displacement occurs in the case of the single-disk implant more than in the case of the double-disk implant. Presented graphs and conclusions are made for the anchorage variant A.

The influence of the anchorage character on the displacement u_z and the strain intensity in dependence on the change of Young's modulus of the cancellous bone can be analyzed on the basis of the following graph in Fig. 9.

For variant C where the implant is placed only in the cancellous bone, it is clear that with the deterioration of the bone quality, the displacement u_z intensively rises. [11] shows the coronoapical tooth displacement in the range 0.05–0.1 mm for the value of loading force 200 N; similarly, [12] presents the implant displacement in the range 0.005–0.06 mm.

In our study, the model was loaded by force of 190 N and for the Young's modulus of the cancellous bone 100-20 MPa, the implant displacement ranged from 0.087 to 0.226 mm. Hence, it is clear that the variant C is according to our biomechanical study not acceptable.

In the case of variant A, displacement for the mentioned loading as well as the material properties ranges from 0.059 to 0.075 mm. Therefore, it can concluded that this range is in accordance with the experimentally obtained values 0.005-0.1 mm. By comparison of the calculated displacements for the variant B (0.063-0.1 mm) with the experimentally obtained ones (0.005-0.1 mm), it was found out that maximal values of both ranges are almost in agreement. Displacements, however, do not tell anything about the behavior of solid bodies. This can be assessed on the basis of strain or strain intensity.

Fig. 9 shows that in the variants B and C, a rapid increase of strain intensity occurs within the decreasing value of Young's modulus. The value of the strain intensity in the case of variant A is almost independent of the change of Young's modulus of the cancellous bone. The foregoing analysis shows that the strain intensity is significantly affected by the cancellous bone quality as well as by the implant anchorage, and the significant influence of the implant configuration can be expected. In the following graphs in Fig. 10, quantities are plotted which will enable us to analyze these influences and dependencies.



Fig.9: Influence of the post-displacement and strain intensity on the Young's modulus for the variants A, B, C

Fig.10: Influence of strain intensity on Young's modulus for variants A, B, C – singledisk and double-disk implant within the first degree of osseointegration

The following graph shows that the dependence of the strain intensity on the Young's modulus of the cancellous bone has the same character for both single-disk and doubledisk implants. The only difference is that the double-disk implant gives smaller values of the strain intensity than the single-disk implant. In the graph, three important regions depending on the values of the strain intensity are highlighted in accordance to Frost^{*}.

The first region with the strain intensity ranging from 0.005 to 0.15 is the region of physiological strains with physiological remodeling of the bone tissue. The second region ranged from 0.15 to 0.30 is the region of mild overloading. The last one is the region of pathological overloading related to the values of the strain intensity higher than 0.3 [13].

From the following graph, it is clear that after the implant is applied and subsequently no osseointegration occurs, the only case of physiological strains is the case of double-disk implant, where the lower disk is implanted on both sides in the cortical bone.

Fig.11: Influence of strain intensity on Young's modulus of cancellous bone for individual degrees of osseointegration, variant A

In the last analysis, attention is paid to the dependence between the degree of osseointegration and the strain intensity both in the single-disk and double-disk implant and for the varying quality of bone tissue expressed by the Young's modulus in the range 20–100 MPa. In graphs in the following Fig. 11, quantities are plotted which enable us to carry out this analysis. Furthermore, regions are highlighted denoting the state of the bone tissue according to Frost.

^{*} Initial works of Dr. Frost which probably describe the essence of this method (no longer noted in later papers) are unavailable to the authors. The authors are aware of this deficiency but yet they used the Frost's assessment for two reasons. The first reason is the fact that there are many papers which refer to Dr. Frost and the second reason is that there is not another work in literature which determines the state of the bone tissue based on the strain intensity.

From the presented dependences it is evident that in the case of variant A with all degrees of the osseointegration and for the Young's modulus of the cancellous bone from 20 to 100 MPa, results lie for both implant types in the region of physiological strains. The only exception is the single-disk implant with the first degree of osseointegration.

10. Discussion

A correlation between the Young's modulus of the cancellous bone and its apparent density has been proved and described in literature [8]. Approximate formulas expressing the correlation mentioned in [17], [18] are part of Fig. 12. Their graphical demonstration for the values relating to the solved problem and for the different parts of the human body is illustrated in Fig. 12 on the left. It is better to use logarithmic coordinates for the Young's modulus in for low values of cancellous bone density, i.e. in our case.

Fig.12: Influence of Young's modulus on the apparent density of cancellous bone for different parts of human body by various authors [8], [17], [18]

Bone density is mostly measured by means of absorption photometry, which uses the energy of two rays (DXA), or by peripheral densitometry. By applying the correlation formulas between the Young's modulus and the apparent density of the bone tissue, the results presented in this study can be expressed as a dependence on this quantity which is measurable with the individual patients (see Fig. 13).

Fig.13: Influence of strain intensity on the apparent density of cancellous bone for variants A, B, C

11. Conclusion

This biomechanical study of the dental disk implant was focused on the stress-strain analysis of the implant and the affected part of the bone tissue. The presented article comprises the first part of the study which is focused on the analysis of bone tissue. The stress-strain analysis of the implant will be presented in the second part of the study.

The conclusion of the first part, using Frost's theory, can be expressed in four points:

- 1. For achieving the physiological strain of the bone tissue, the implant anchorage has the greatest influence. Only variant A and the double-disk implant guarantees the possibility of immediate loading of the implant after the application regardless of the quality of the bone tissue (see Fig. 10).
- 2. If a deviation to the anchorage A occurs, it is necessary to create conditions for osseointegration (see Fig. 11).
- 3. The displacement u_z is an important deformation quantity which is measurable, but it is always necessary to also add the strain analysis. Despite the negligible difference in displacements in the case of the variants A and B, the difference in the strain intensity is significant (see Fig. 9, red and green curves – continuous and dashed).
- 4. By application of the correlation formulas between the Young's modulus and the apparent density of the bone tissue (the latter is measurable), the results presented in this study can be expressed as a dependence on this quantity.

These conclusions were based on the biomechanical study. The problem of the interaction of the implant with the bone is a complex problem, which has other significant aspects – clinical, biological and biochemical, etc. For complex assessment, all related factors must be considered.

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