Research on the biomechanical behavior of dental implants

A Rohan and M Baritz

Design Product and Environment Faculty, University Transilvania from Brasov

E-mail: andreea.rohan@student.unitbv.ro

Abstract. As shown in a large series of researches, dental implants are generally made of titanium because this material allows a stable and functional connection between the bone and the contact surface of the implant. From the point of view of the mechanical behavior of dental implants, it was found that too large or incorrectly directed forces developed in the mastication process can change these connections at the same time as affecting the osseointegration process, compromising the stability of the implant. That is why modelling the behavior of dental implants represents a pre-analysis solution to understand the effect of the correct development of the mastication process. In the first part of the paper a series of researches are presented and their results regarding the importance and effect of the dimensions of dental implants on their behavior. The second part of the paper presents the analysis scheme on dental implants and establishes the procedures for making the 3D model with convertible properties compared to the real implant. The third part of the paper mentions some aspects related to the design of the experimental installation and the design of dental implant testing procedures. The final part of the paper presents the observations and conclusions of this approach of developing a system for behavioral analysis of dental implants.

1. Introduction

The restauration and recovery process of the bone that makes up the orofacial system (through all its components) presents a permanent technical and technological challenge for specialists, especially when it comes to finding materials and techniques for making dental implants. A very important condition underlying the choice of a material for making dental implants is its biocompatibility with the anatomical and physiological characteristics of the oral cavity.

Due to the fact that a dental implant will be subjected to stress in the process of mastication at high compressive and frictional forces and will also operate in a dynamic regime (both biomechanically and biochemically), these parts must be processed using advanced technologies to obtain and maintain the dimensional and mechanical properties for as long as possible.

In order to fulfill these primary requirements, dental implants must meet the following fundamental characteristics [1]:

- the implant's material must not produce harmful toxicological or allergic effects to the patient or operator;
- the physical and mechanical properties of the material should withstand the functional load and the difficult oral environment (e.g., tensile strength, modulus of elasticity, solubility, thermal conduction); the manufacturing technology should be inexpensive and also be feasible for both the medical and technical specialist;

- the shape, color and quality of the implant's material should increase the aesthetic result of the teeth and passively match the rest of the teeth so as not to cause wear at the prosthesis-implant interface;
- the material must allow the use of appropriate oral hygiene measures and prohibit or eliminate the accumulation of oral plaque; the implant should give the opportunity to be repaired when an adverse reaction occurs due to the used material;

Figure 1. Dental implant [2]

These characteristics take form in the following parameters:

- the modulus of elasticity is important in choosing the material that has a modulus of elasticity comparable to bone (18 GPa), therefore it must be selected to ensure a more even distribution of stress at the implant and to minimize movement relative to the bone interface of the implant.
- the tensile, compressive and shear strength of a material should be high to prevent fractures and improve functional stability.
- the fatigue strength of a material must allow the prevention of brittle fractures under cyclic loading.
- in the case of ductility, this parameter must have a minimum value of 8% for the dental implant, the limit being necessary for the contouring and modeling of an implant.
- hardness and strength - allows the reduction of wear through increasing of hardness of the implant's material and prevents fractures of implants.
- surface tension and surface energy determine the wettability of the implant by blood-fluid wetting and by the cleanliness of the surface of the implant; osteoblasts have improved adhesion to the implant surface, and surface energy also affects protein adsorption.
- the roughness of the surface through its changes at the contact surfaces' level influences the response of the tissues.

To perform a general analysis, the implant's surfaces were classified according to different criteria, such as roughness, texture, and irregular orientation. Thus, from this point of view, the researchers divided the implant surfaces according to the surface roughness as: minimum rough, intermediate rough, rough major.

Furthermore, the surfaces can be analyzed according to their texture and can be classified into concave texture (mainly by additive treatments such as hydroxyapatite-HA coating and titanium plasma spraying), convex texture (mainly by subtractive treatment, such as engraving and sandblasting). In addition, the implant surface can be classified according to the orientation of the surface irregularities into isotropic surfaces (similar topography independent of the measuring direction) and into anisotropic surfaces (clear directionality and varies considerably in roughness) [1]. Another very important aspect in the construction of dental implants is choosing the appropriate material from all points of view: dimensional, biomechanical, surface quality and obviously biocompatibility with the orofacial system, in all its component parts.

The principles of designing an implant must be compatible with the physical properties of the material used to make the body of the dental implant. The materials used to make dental implants can be classified according to their chemical composition or the biological responses when implanted [3].

In terms of materials, dental implants can be made of metals (titanium and titanium alloys, chromium cobalt alloy, gold alloys, tantalum), ceramics (alumina, hydroxyapatite, carbon, bio glass, zirconia, zirconium hardened alumina) or polymers (polymethacrylate, polytetrafluoroethylene).

Each of the categories of materials possible to be used for the construction of the dental implant have been studied both as a material for the structural base and as a coating material leading to the improvement of the osteosynthesis process. Among the most used calcium phosphate coating materials are dense hydroxyapatite and fluorapatite, because these coatings contain partially amorphous regions, but at the same time, preserving the crystalline regions. In addition, the denser coatings are also characterized by higher strength properties and lower solubility [4][5].

2. Theoretical aspects of dental implants stability

One of the most important problems that manifests itself at the level of the dental implant in contact with the facial bone structure of the patient is the process of osseointegration which is in turn supported by the stability of the implant. The primary stability of implants is considered as an essential factor for achieving a proper osseointegration process [6]. Micro-movements higher than the threshold of 50 to 100 μm can lead to the formation of fibrous tissue at the bone-implant interface.

As shown in the research studies, a series of techniques for assessing the level of stability have been initiated and developed, quantifying this level by dental implant stability coefficients (ISQ). Values of this coefficient between 1 and 100 indicate (values at the upper limit of the range) a high level of stability. The variation of the values of the stability coefficient [7][8] is determined by a series of factors such as: the quality and quantity of bone structure in which the implantation is performed, the geometric parameters of the implant (shape, diameters, lengths) and the surgical placement techniques. of the dental implant [9][10].

From a mechanical point of view, any body, including the mandible, obeys Newton's laws, the movements being caused by forces acting on the mandible. For every linear force (F_x, F_y, F_z) there is a moment (angular) or a couple ($M_{azimuth}$, $M_{elevation}$, $M_{rotation}$), the resultant forces and moments generating acceleration according to Newton’s second law [11]. The moment of inertia along an axis is defined as the sum of the mass of each particle multiplied by the distance between the particle and the relevant axis squared, for a mandible of about 0.44 kg, the moment of inertia being estimated at about 8,6 kg.cm^2, 2,9 kg.cm^2 and 6,1 kg.cm^2 for $I_{azimuth}$ (axis z), $I_{elevation}$ (axis y) and $I_{rotation}$ (axis x) [11].

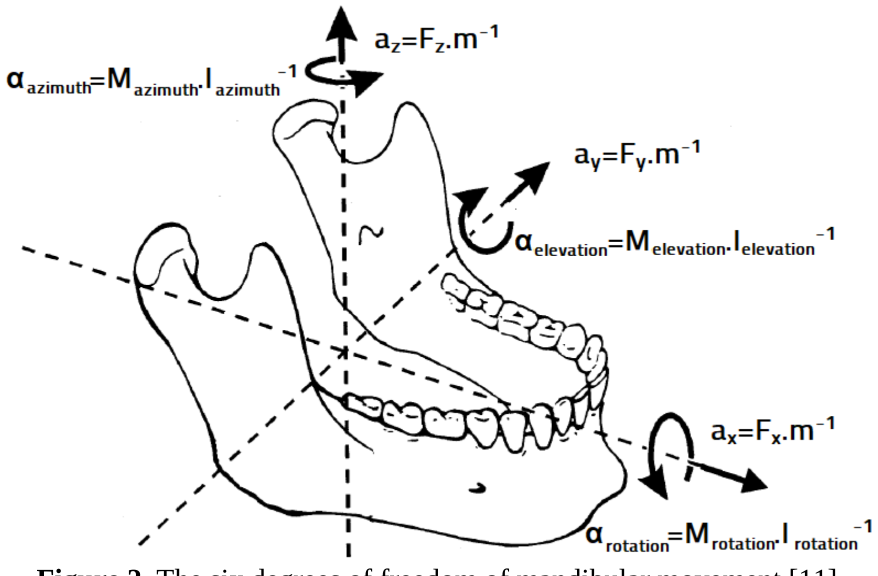

Figure 2. The six degrees of freedom of mandibular movement [11]

About 70% of the population United States population has at least one missing tooth [12]. The first missing teeth usually happen between the ages of 35 and 54 [12]. One of the treatment options for missing teeth is a simple dental implant, which is faster, simpler and cheaper to produce and implant [12]. Because this type of implant has the highest success rate for replacing a single missing tooth, it is the most widely used treatment in this case, especially if endodontics of the adjacent tooth is desired or it needs a crown for support [12]. Thus, the simple dental implant has the highest survival rate for the replacement of a single tooth, has the highest survival rate for adjacent teeth and the lowest complication rate [12].

Figure 3. Types of designs for dental implants [12]

From the point of view of the materials used in dental implantology, there are three main basic groups: metals, plastics and silicate materials [14].

Metals and alloys make possible the development of precise and complex shapes of implant structures, in modern implantology there are different types of alloys being used based on metals such as cobalt, chromium, nickel, gold, silver, titanium, palladium, platinum and others [14]. Their disadvantages include the relatively unpleasant aesthetic appearance, as well as the greater possibility of adverse allergic reactions [14].

Dental plastics, based on polyacrylate, are a relatively new option, which has the advantages of being polymerized in the patient's oral cavity, being manufactured in very complex forms and it can be given a relatively simple natural appearance [14]. Polymers are weaker than metals and although they are easier to manufacture, they can only be used for a limited time and for relatively small loads [14].

Silicate materials were developed taking into account the composition of tooth enamel, consisting of 96% inorganic matter (hydroxyapatite ($Ca10(OH)2(PO4)6$) represents the majority of the inorganic part) and 4% organic matter and water [14]. The first form in which they appeared was the porcelain dental implants formed by casting, but they also developed over time pressed prostheses based on ceramic powder [14].

Titanium and titanium alloys have become the preferred materials for the production of dental implants, pure titanium creating an oxide layer on the surface immediately after exposure to air (9-10 seconds), which can reach 2-10 nm in a second [14]. This stable titanium oxide surface is biocompatible and has high corrosion resistance, high passivity and high chemical resistance, the modulus of elasticity of titanium and its alloys being comparable to that of human bone [14].

To understand the connection between the distribution of occlusal force and clenching strength, we follow the results of mechanical experiments which record a large number of variables that characterize the two elements [15]. Thus, the number of occlusal contacts increases linearly with the clenching strength, the distribution of the occlusal force having the highest values in the molar region [15].

In the process of implanting and determining the stability of the dental implant, osseointegration must also be taken into account, determined by several factors. Osteointegration is a measure of the stability of an implant, which takes place in two stages: primary and secondary [16].

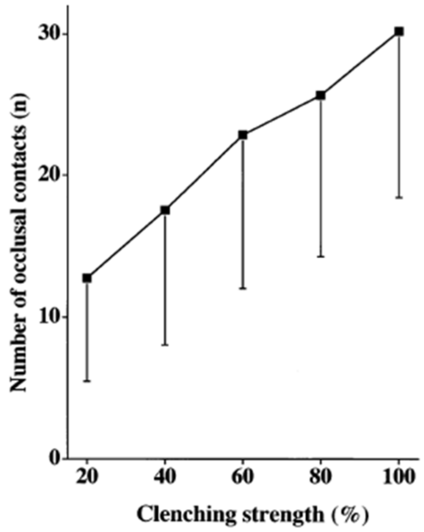

Figure 4. The number of occlusal contacts at different levels of clenching [16]

Mechanical engagement is the source of primary stability, especially the contact with cortical bone [16]. Secondary stability means the process of bone regeneration and remodeling that provides biological stability [16]. Although primary stability is responsible for good secondary stability, the latter is the one that dictates the functional loading time [16].

Among the factors that affect the primary stability are: the quality and quantity of bone tissue, surgical technique, type of implant (geometry, length, surface characteristics) [16]. The elements that affect the secondary stability are: the primary stability, the modeling and remodeling of the bone and the surface conditions of the implant [16].

3. Experimental setup

Because working with in vivo dental implants presents a high difficulty [13] and also subjectivity on the part of participants, in vitro experiments can be used, where different polymer samples with different densities can be used for insertion that simulate the structure of the trabecular bone [13], as well as a computer simulation component, represented by finite element analysis. In the case of digital simulation, the properties of the material in which the fixture is made will be taken into account so that they are as close as possible to those of the trabecular bone, namely: density, Young's modulus (modulus of elasticity), tensile / compressive strength and Poisson's ratio [13].

The determination of maximum masticatory force depends on factors such as occlusion type, age and sex [17]. Stabilization of the maximum voluntary biting force for subjects with full and normal dentition occurs faster in male or older subjects, subjects aged between 15-18 showing a rapid increase in strength [17]. These elements are important due to the change in the characteristics of bone and muscle tissues in the process of aging [17].

For the simulation and finite element analysis the software SolidWorks was chosen (part and assembly modules). When choosing the properties, for the implant we chose a pre-defined material, Titanium Grade 4 UNS R50700 (CP TI75A), for the trabecular bone we used median dates from dedicated research [18]. The differences between individuals with normal dentition and partial dentition is insignificant [18]. The density of mandibular specimens was determined to be in the 0,85 to 1,53 g/cm^3 range, and the mean stiffness value was determined to be 96,2 MPa (approximated in this simulation to 96 MPa).

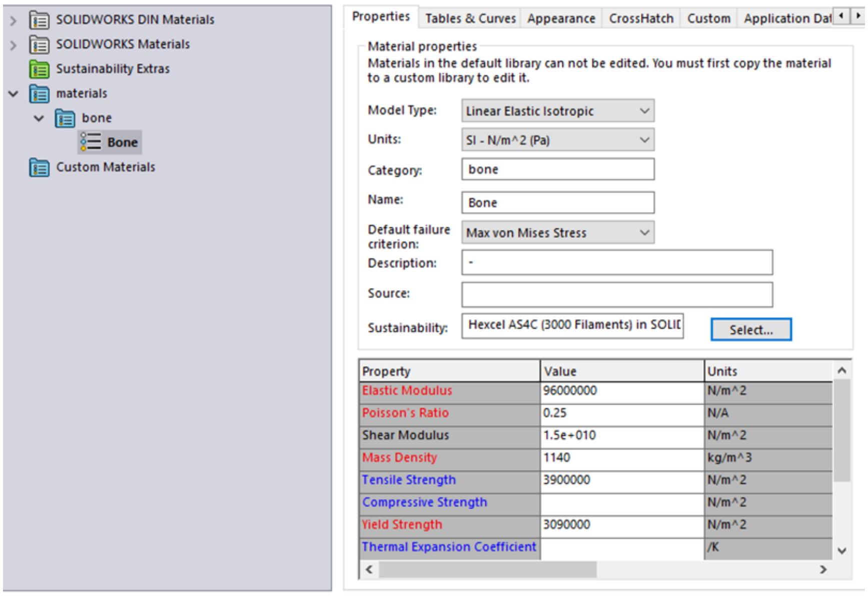

Figure 5. Characteristics used for the simulated trabecular bone

The implant was inserted in the pre-defined material, the connection of the two being made with a soldering rigid material from the list of properties offered by the software in the assembly module. The next step was to choose the fixtures, the contacts and the forces that are applied (the arbitrary value of 400 N was chosen, being considered a maximum force or a force that can even exceed the maximum value depending on the individual). To observe and understand the behavior of the implant, a cross section of the entire assembly was made both before and during the simulation. The analysis was static, the maximum deformation temperature being calculated by the software as 298 ° K (≈ 25 ° C).

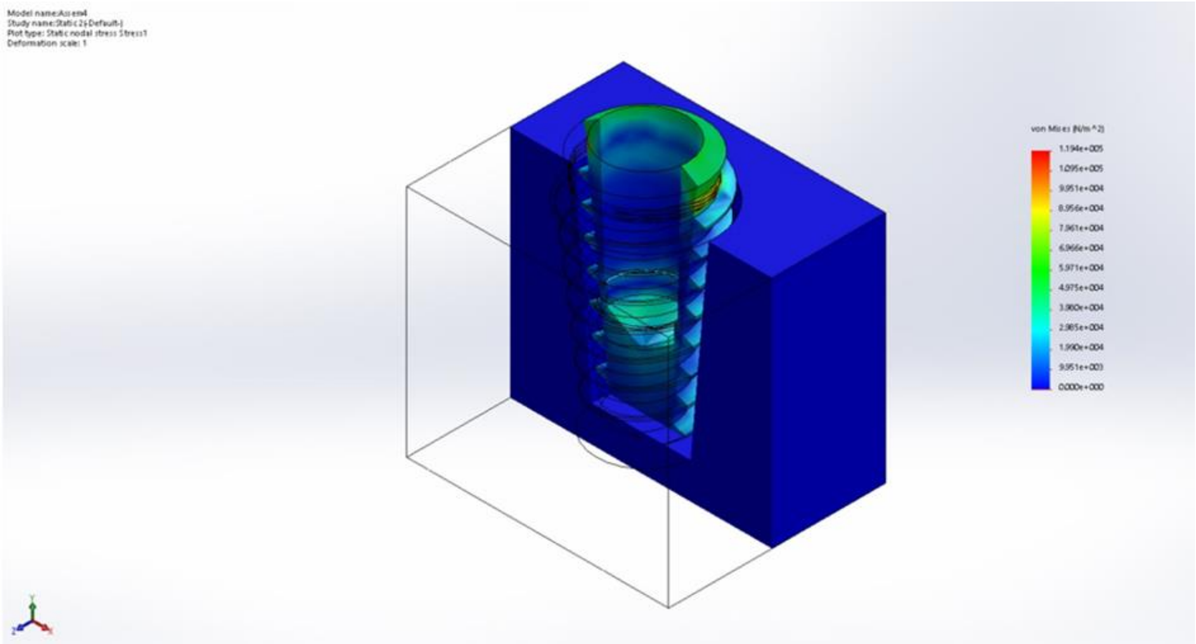

Figure 6. The effect of von Mises stress, cross section

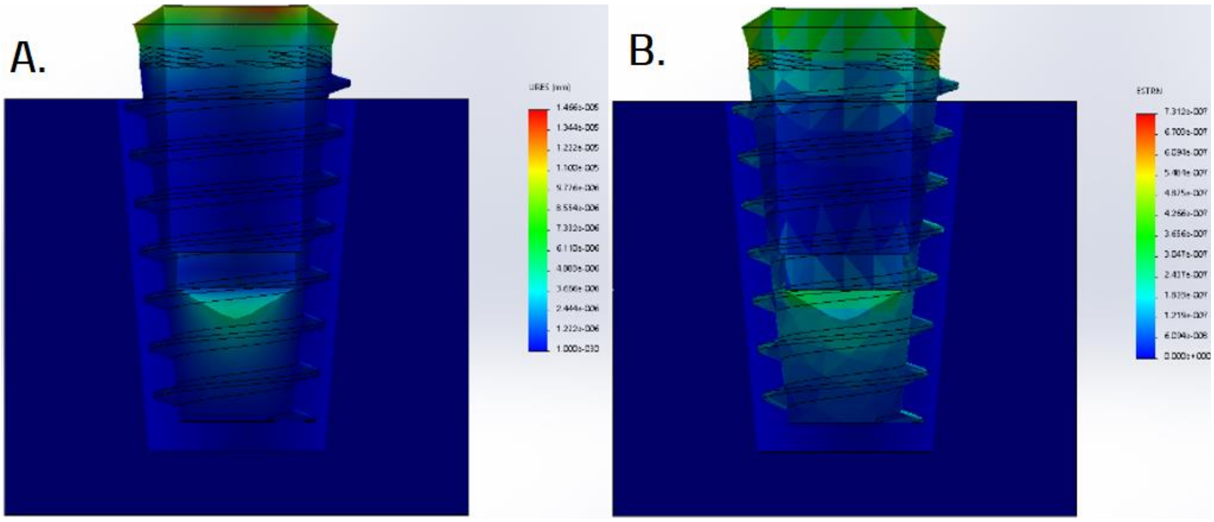

Figure 7. A. Displacement, cross section **B.** Stress, cross section

4. Results and conclusions

The mechanical testing of dental implants involves understanding all stages of the masticatory process, as well as how the morphological characteristics of individuals affect the behavior of implanted bodies. In order to understand this behavior, an ideal case was chosen, simulated in a CAD modelling software on which the finite element analysis was performed.

All the elements subjected to the test show that the movement and stress of the implant appear on the outside in the upper area, and on the inside in the lower area, i.e., the parts used to assemble a composite implant. For this reason, it is important to choose implantable elements that work perfectly with each other, especially for very small implants such as dental ones, but also the assessment of the general health and tissues of patients must be done correctly for in vivo cases.

References

[1] Saini M, Singh Y, Arora P, Arora V and Jain K 2015 Implant biomaterials: A comprehensive review *World J Clin Cases* vol 3(1) pp 52–57

[2] https://gpsdentalsa.com/blog/tag/dental-implants/ [Accessed April 2021]

[3] Osman R B and Swain M V 2015 A critical review of dental implant materials with an emphasis on titanium versus zirconia *Materials* vol 8(3): pp 932–958

[4] Kohal R J, Att W, Bächle M and Butz F 2008 Ceramic abutments and ceramic oral implants. An update *Periodontology 2000* vol 47 pp 224–243

[5] Tinsley D, Watson C and Russell J 2001 A comparison of hydroxyapatite coated implant retained fixed and removable mandibular prostheses over 4 to 6 years *Clin Oral Implants Res* vol 12 pp 159–166

[6] Barikani H, Rashtak S, Akbari S, Badri S, Daneshparvar N and Rokn A 2013 The Effect of Implant Length and Diameter on the Primary Stability in Different Bone Types *Journal of Dentistry, Tehran University of Medical Sciences* vol 10(5)

[7] Sencimen M, Gulses A, Ozen J, Dergin C, Okcu K M, Ayyildiz S and Altug H A 2011 Early detection of alterations in the resonance frequency assess-ment of oral implant stability on various bone types: a clinical study *J Oral Implantol* vol 37(4) pp 411-419

[8] Rokn A R, Ghahroudi A A R, Mesgarzadeh A, Miremadi A and Yaghoobi S 2011 Evaluation of Stability Changes in Tapered and Parallel Wall Implants: A Human Clinical Trial, *J Dent (Tehran)* vol 8(4) pp 186-200

[9] Sabeva E 2018 Comparison between the influence of implant diameter and implant length on the primary stability *Scripta Scientifica Medicinae Dentalis* vol 4(2) p 36

[10] Takahashi K, Shiraishi N, Ishiko-Uzuka R, Anada T, Suzuki O, Masumoto H and Sasaki K 2015 Biomechanical Evaluation of Ti-Nb-Sn Alloy Implants with a Low Young's Modulus *International Journal of Molecular Sciences* vol 16(2) pp 5779-5788

[11] Koolstra J H Dynamics of the Human Masticatory System 2002 *Critical Review in Oral Biology & Medicine* vol 13(4) pp 366-376

[12] Misch C E 2015 *Dental Implant Prosthetics 2nd edition* (Elsevier Mosby)

[13] Bicudo P, Reis J, Deus A M, Reis L and Vaz M F 2016 Performance evaluation of dental implants: An experimental and numerical simulation study *Theoretical and Applied Fracture Mechanics* vol 85 pp 74-83

[14] Shalukho N M, Kuz'menkov M I and Bogdanovich I A 2012 Materials for Dental Prosthetics *Glass and Ceramics (English translation of Stelko I Keramika)* vol 69(7-8) pp 243-245

[15] Kumagai H, Suzuki T, Hamada T, Sondang P, Fujitani M and Nikawa H 1999 Occlusal force distribution on the dental arch during various levels of clenching *Journal of Oral Rehabilitation* vol 26(12) pp 932-935

[16] Atsumi M, Park S and Wang H 2007 Methods Used to Assess Implant Stability: Current Status *The International Journal of Oral & Maxillofacial Implants* vol 22(5) pp 743-754

[17] Varga S, Spalj S, Varga M L, Milosevic S A, Mestrovic S and Slaj M 2010 Maximum voluntary molar bite force in subjects with normal occlusion, *European Journal of Orthodontics* vol 33(4) pp 427-433

[18] Misch C E, Qu Z and Bidez M W 1999 Mechanical Properties of Trabecular Bone in the Human Mandible: Implications for Dental Implant Treatment Planning and Surgical Placement, *Journal of Oral and Maxillofacial Surgery* vol 57(6) pp 700-706

Acknowledgments

In these experiments, we have developed the investigations with equipment from Medical Engineering Laboratory and the research is part of Andreea Rohan's student diploma project work in the Transilvania University from Brasov.