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HYDROXYAPATITE STRUCTURES AND NUMERICAL ANALYSIS OF THE GEOMETRIC CHARACTERISTICS OF THE LOWER JAW FIXATION PLATES

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Abstract. *Bone defect reparation can be successfully performed with biomaterials based on synthetic hydroxyapatite (HAP). In addition to collagen, hydroxyapatite is the basic structure of bone tissue and it was expected to have excellent biocompatibility. This study presents an analysis of the properties of HAP, its biocompatibility as well as its other properties that scientists tried to modify.*
In this study, we've listed some examples of HAP implantation and typical problems during system implementation. Using the finite element method, the influence of the geometry of the fixation plates on the stress distribution was analyzed. The analysis showed that the best characteristics were shown by large surface fixation plates, but due to the problem of connecting in the bone-implant system, the design of the minimum surface plate with two rows of screws was selected.
Keywords: *hydroxyapatite, finite element method, fixation plates, polylactide (PLLA), numerical analysis*

1. BIOCERAMICS AND APATITE STRUCTURES

Biomaterials are materials that are designed to replace parts of the living system or fulfill the appropriate function a certain period of time within the body. Bioceramics are used in a wide range of medical systems. According to the type of interaction with surrounding tissue, bioceramics can be classified into: bioactive, bioresorbable, and bioinert. Bioactive and bioinert ceramics can remain in the human body whole lifetime without resorption. Bioresorbable ceramics have the ability to gradually degradate in the body, which is also their key advantage. Bioresorbility has been widely used in the field of tissue engineering and can be time-adjusted so that the material gradually degradate by the growth rate of newly formed bone tissue. [1]
The most frequently used bioactive ceramics are hydroxyapatite (HAP) and bioactive glass. It has not yet been fully explained why bioactive ceramics connect directly to the bone. Reason is that apatite is the dominant inorganic phase of hard tissues.
The cortical bone is a composite made of collagen and apatite. Collagen provides good resistance to stretching and apatite structure to pressure.HAP is the dominant inorganic component of hard tissues in the human body, such as teeth and bones, and it is a class of bioactive ceramics. Bone tissue consists of calcium phosphate (69%), collagen (20%), water (9%) and other elements (2%). Hydroxyapatite widely used in research for reparation of damaged tissues. The term HAP usually refers to $Ca_{10}(PO_4)_6(OH)_2$, although the term "apatite"

originally means a much broader class. The general formula for apatite is given by: $M_{10}(RO_4)_6X_2$, M=Ca, Na, K, Mg, Sr; RO_4=PO_4, HPO_4, CO_3 i X=OH, Cl, F, CO_3. [1]
There are three types of ceramics used to reconstruct bone defects - dense, porous and granular. Dense ceramics are used in places where high mechanical pressures are required. Like dense ceramics, and porous ceramics are used to reconstr large bone defects. The construction of dense ceramics provides physical strength, while porous ceramics have property to provide flexibility - it is possible to shape implant during surgery for better adaptation to the position where implantation should be performed. Granular ceramics are most often used in the form of fillings to fill defects. [2]

Porous HAP ceramics are primarily used as a replacement for damaged bone tissue because the pores allow connecting of the contact surfaces. It is obvious that reducing the density of the implant reduces mechanical properties and this type of material can't be used when are required implants with great mechanical properties. The sintering process enables the production of dense HAP ceramics with high mechanical strength values only if the HAP initial powder have the molar ratio Ca / P = 1.67. Sintering will cause a decrease in pore size which will directly change mechanical properties. [2]

2. POLYMER BIOMATERIALS AND POLYLACTIDE (PLA)

Polymers are high-molecular-weight chain molecules, consisting of a large number of smaller units called mers. Polylactide (PLA) is characterized by being completely non-toxic, and this has been confirmed by studies that have observed products of degradation. Mechanical properties depend on the material structure and can vary in a wider range (elastic modulus 0.5, -10GPa). PLLA with high porosity (93%) in the form of foam with pore size of about 500µm has found wide use in tissue engineering as a polymer carrier, which primarily provides good differentiation and adherence of osteoblasts in *in vivo* cultures.
The combination of HAP and bioresorbable polymers represents a new concept in the design of composite materials. This biomaterial can be considered "alive" because of its characteristic that allows it to gradually change its morphological properties in a previously programmed time period. The basic idea is that the bioresorption component (PLLA) gradually decomposes and make places the newly formed bone tissue. Studies have shown that the combination of HAP and PLLA results in the creation of a greater number of osteoblasts than case with only HAP material(Figure 1).

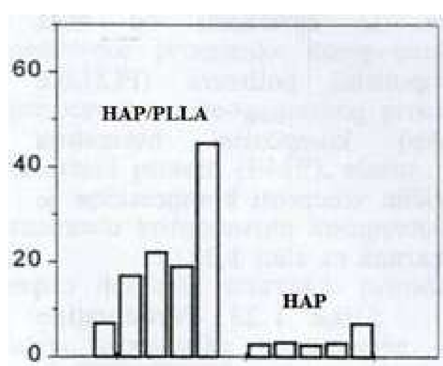

Figure 1: Increase in the number of cells on the contact surfaces using PLLA polymers [2]

As the number of osteoblasts increases, the reparation process is accelerated. Values on vertical axis is related to number of adherence cells. The main difficulty in developing porous

materials as a replacement of hard bone tissue was that porous materials (HAP) didn't have satisfactory mechanical properties to replace bones. In order to achieve the optimum distribution of load that occur during stress, it is necessary that the composite biomaterial HAP / PLLA possesses mechanical properties very similar to the bones. [2]
The experiments have shown that different values of mechanical characteristics can be achieved by varying the mass fraction of HAP and PLLA in the composite. By increasing the proportion of the HAP component, the values of compression and bending strength increase as well as the values of their modules. [2]

3. COMPOSITE - HYDROXYAPATITE / LIGNIN COATING

By depositing thin layers of HAP on substrates of metals, glass or polymer, surface modification is achieved such that it improves biocompatibility and other properties of material. Increased biocompatibility is achieved by depositing thin layers on metal surfaces, but also the reduced release of oxides of metal and ions into the surrounding tissue.
HAP is used in most cases in the form of coatings or composites. The reason for this is its relatively poor mechanical properties. Titanium and titanium alloys have been proved to be excellent for implants because of their good strength properties. The coatings of hydroxyapatite are used to coat metal implants, because at the same time we achieve a better biological function of the implant (HAP) and better mechanical properties (metal). Similarity with bone tissue allows hydroxyapatite to form direct chemical bonds with the surrounding tissue. [3]
As the studies have shown, hydroxyapatite is very brittle material and shows the property of significant compression during the sintering process. For this reason, lignin was studied as the most commonly used natural polymer in the world. Lignin is suitable as a coating material due to the properties of forming stable mixtures. Lignin enabled the increase in thermal stability of hydroxyapatite during the sintering process. [3]

4. NANOTECHNOLOGICAL FUNCTIONALIZATION OF THE COATING

Nanotechnology can be defined as a multidisciplinary science that includes physics, chemistry, biology, as well as a wide range of engineering disciplines. Surface functionalization can be explained as a way of establishing new which have the task of fulfilling the desired requirements. Functional surfaces consist of new or modified chemical groups and/or morphologies that determine the interaction of materials with the environment.
In accordance with the principle that biological implants are put in a very active environment of the organism, special attention is paid to anticorrosion protection. Corrosion is a natural process that changing metal in a chemically stable form, such as, for example, oxides, hydroxides and sulfides. A feature of corrosion is the gradual degradation of the structure which leading to a potential failure of the function. [4]
The two main strategies used to form the desired coating characteristics include encapsulation (filling the matrix of the carrier with functionally active components) and manipulating with the composition matrix of the coating with the addition of few surface functional groups. The anticorrosion principle is shown in Figure 2. [5]

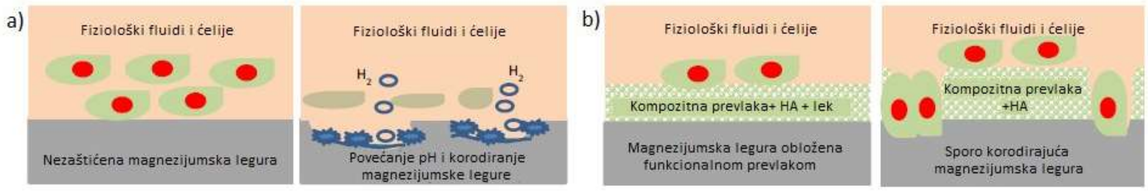

Figure 2: Corrosion resistance of non-coated (a) or coated magnesium alloy (b) [6]

5. APPLICATION OF HAP STRUCTURES - DENTAL IMPLANTOLOGY

There are three ways of connection between the implant and the bones. The first method known as osteointegration involves physical binding without connective tissue between the bone and the implant. The second way is called fibrointegration and it implies the existence of connective tissue in the contact of the two systems. The third way is called biointegration and implies chemical bonding of bones and implants. [1]

We will observe the process of implantation of dental implants coated with apatite (Figure 3). The process can be done during one or two stages. The implant is placed in the jaw during an initial operation. The oral mucosa is sewn at the end of the surgery so that the implant is completely covered (3-6 months) and protected from external influences. This period is really important because implant have enough time for connecting to the bone. During the second penetration through the gingiva is necessary in order to connect the visual part of the implant with the base. [1]

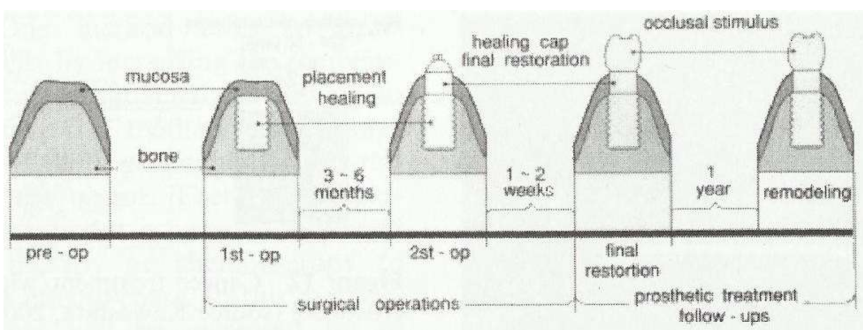

Figure 3. A schematic diagram of the treatment in two phases [1]

6. APPLICATION OF FEA TO THE MODELING OF JAW FIXATION PLATES

The application of finite element method has some drawbacks. The stress values obtained by this method don't necessarily correspond to the real state. In this study, some approximations were applied, both on the model and in the type and characteristics of the material. In the finite element method, bones are modeled as isotropic although they have an anisotropic structure.

With few approximations, the model of the mandible is made. On that model we installed the fixing plates, so that we can numerically get the data which type of fixation plates best carries the load. Figure 4 shows a way of defining the boundary conditions for the observed lower jaw model.

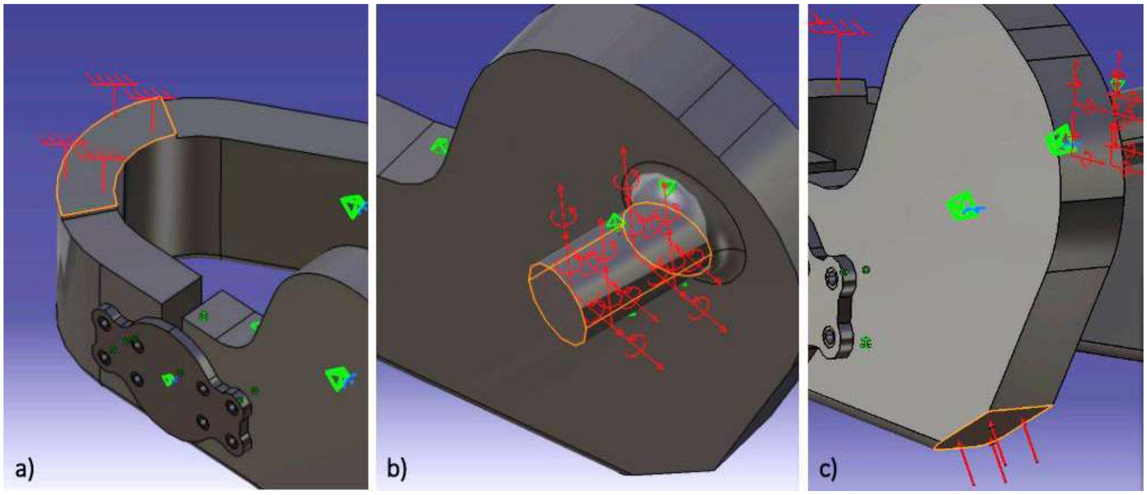

Figure 4. Example of setting fixations and force properties

Figure 4a shows that the contact between the lower and upper jaws is approximated by small surface. The contact surface is positioned on the front of the mandible so that the tested plates will suffer a higher maximum load. Figure 4b shows that the shaft is axially movable while at the orthogonal level it is limited. Figure 4c shows the position of the load action which represents the approximation of the action of the jaw muscle, that is, the occlusion force. When displaying the results, a scale is shown indicating deformations in order to make the changes visible. The maximum value is shown in red and is located mainly on the part of the tile at the fracture point of the mandible. The least load suffers from the part of the tile that is most distant from the location of force. The surface of the contact directly affects the load distribution, but on the other hand leads to a potential problem of relieving the implant because the jaw bone is not ideal as an approximated model.
A total of eight budget models have been produced, and the choice of models has been taken from reference literature [10, 11, 12, 13]. Several forms of plates are in clinical use, but here we have some models of new design.

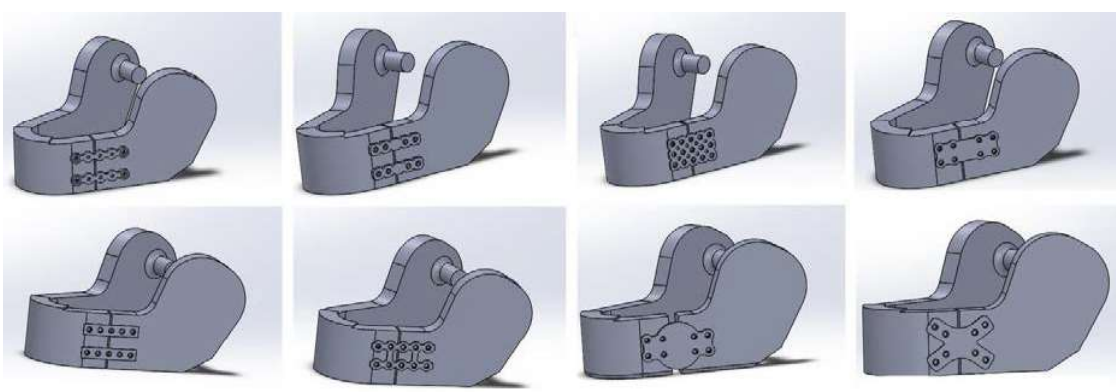

Figure 5: Asemblies of mandible and fixation plates

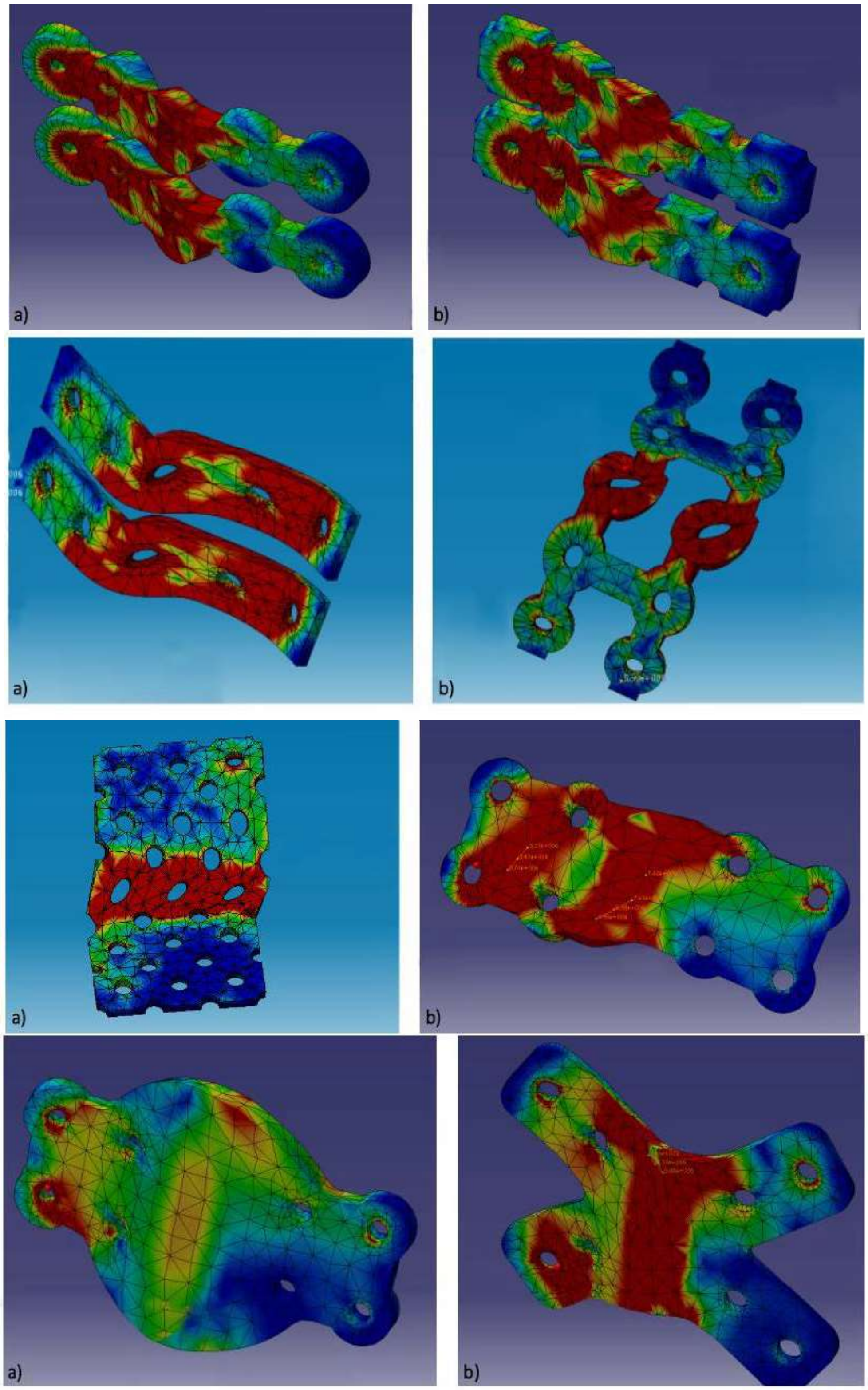

Figure 6: Examples of model test plates

7. ANALYSIS OF RESULTS AND DISCUSSIONS

From all of the above, it can be concluded that the fixation plate shown in the numerical model 7 has a more even distribution of the stress compared to the other plates. Its disadvantage is actually what gives it a good distribution of stress - a large surface. In nature, the mandible is not an ideal flat surface as in this approximated model. This can lead to the loosening of the bolts, which later leads to the failure of the implant.
The following models that showed the best stress distribution characteristics were models 6 and 8. The results of the maximum stress were almost identical, 19 and 20 MPa. The production of the model 8 is a slightly more complicated, and due to an identical stress distribution, we can concentrate our attention on model 6. Figure 7 shows a united graphic representation of the maximum stress values for the tested fixation plate models.

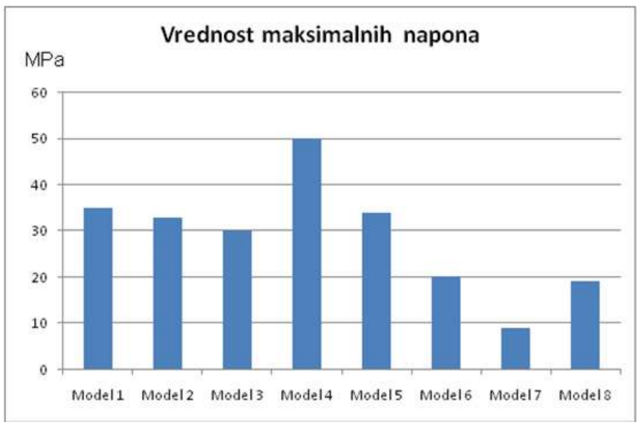

Figure 7: Graphic display of the maximum voltage values for all tested models

As previously said, this model is expected to show significantly better characteristics than any model of separated plates (Models 1-3). The contact area of the mandible and fixation plate is relatively small compared to model 7, because of that it can be expected that there will be no problems with the implant-bone system and there will be no loosening and potential failure of the implant.
The difference in stress between fixation plate number 6 and the separated plates is 43, 39, 32, 60, 42% respectively. This type of plates would be relatively easy to fabricate, and due to the improved properties in relation to the separated plates, it should definitely be a design that needs to be tended.

8. CONCLUSION

Using the finite element methods, the analysis of different forms of fixing plates was successfully presented. The obtained values of the maximum tension on the plates should be taken carefully, because of making few approximations in the design of the model. However, the accuracy of the relationship of the maximum voltage is relevant, and therefore we can conclude that the separate plates carry smaller loads but better fit to the bone. Plates with larger surface achieve better distribution of stress and the difficult contact with the bone tissue, naturally unevenly, can lead to loosening and potential cancellation. The proposed solution is presented as a fused plate with the smallest overall surface (model 6)

REFERENCES

1. Y. Mai, S. Teoh, Comprehensive structural Integrity- Fracture of Materials from nano to Macro, 2003.
2. Nenad Ignjatović, Synthesis and designing of the structure and properties of composite biomaterials hydroxyapatite-polylactides, PhD, Faculty of Technology and Metallurgy, University of Belgrade, 2001.
3. Rade Surudžić, Sanja Eraković, Vesna Mišković-Stanković, Synthesis and characterization of sintered hydroxyapatite/lignin coatings on titanium, Hem. ind. 66(2), 187–192, 2012.
4. R. S. Abdel Hameed, Abd-Alhakeem, Nano-composite as corrosion inhibitors for steel alloys in different corrosive media, Advances in applied science research, 4(3):126-129, ISSN: 0976-8610, 2013.
5. Dolai S, Khanna AS. Importance of Nanoparticles in the Development of Durable Multi- functional and Smart Organic Coatings. Nano Res Appl. 2016.
6. M. Montemor, Functional and smart coatings for corrosion protection, Surfaceand Coatings Technology, Volume 258, Pages 17-37, 15 November 2014.
7. Rainer Schmelzeisen, Terry McIff, Berton Rahn, Further development of titanium miniplate fixation for mandibular fractures. Experience gained and questions raised from a prospective clinical pilot study with 2.0 mm fixation plates, Journal of cranio-maxillo-facial surgery, Volume 20, Issue 6, Pages 251–256, September 1992.
8. Robert M.Laughlin, Michael S.Block, RandallWilk, Randolph B.Malloy, John N.Kent, Resorbable Plates for the Fixation of Mandibular Fractures: A Prospective Study, Journal of Oral and Maxillofacial Surgery, Volume 65, Issue 1, Pages 89–96 , January 2007.
9. Yonghong Zhao, Yi Yang,Zongli Gao,Weiming Wu, Weiwei He, Tiancheng Zhao, Treatment of traumatic sternal fractures with titanium plate internal fixation: a retrospective study, Journal of Cardiothoracic Surgery, 12: 22, April 2017.
10. Adel Alhalawani, A review of sternal closure techniques, Ryerson University, Department of Mechanical Engineering, Journal of biomaterials application, 28(4), 483-497, 2013.