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NUMERICAL ANALYSIS OF THE MANDIBULAR RECONSTRUCTION WITH THE USE OF AUTOGENOUS BONE GRAFT AND DENTAL IMPLANTS

ANALIZA NUMERYCZNA REKONSTRUKCJI ŻUCHWY PRZESZCZEPEM AUTOGENNYM Z WPROWADZONYMI IMPLANTAMI STOMATOLOGICZNYMI

A b s t r a c t

The article refers to some issues of the mandible reconstruction in the region of chin with the method involving dental implants introduced for teeth restoration. 12 models are created, which take into account three different graft materials (iliac crest, fibula and rib) and two various implant lengths (13 and 18 mm). The authors try to answer the question how the parameters of the introduced implants affect the distribution of the strain intensity in the mandible, both in the implantation area and at its border with autogenous graft. Also, the distribution of equivalent stress in the reconstruction plate and dental implants is analyzed.

Keywords: mandibular reconstruction, autogenous grafts, dental implants, FEA

S t r e s z c z e n i e

Praca dotyczy problematyki rekonstrukcji żuchwy w rejonie bródki z wykorzystaniem metody polegającej na wprowadzeniu implantów stomatologicznych pod odbudowę uzębienia. W artykule stworzono 12 modeli uwzględniających zastosowanie trzech różnych materiałów na przeszczep (kości biodrowej, strzałkowej i żebra) oraz dwie różne długości umieszczonych implantów (13 i 18 mm). Autorzy podjęli próbę odpowiedzi na pytanie, w jaki sposób parametry wprowadzonych implantów wpływają na rozkład intensywności odkształcenia w kości żuchwy w obszarze implantacji oraz na granicy z przeszczepem autogennym. Analizie poddano również rozkład naprężenia zredukowanego w płycie rekonstrukcyjnej oraz implantach stomatologicznych.

Słowa kluczowe: rekonstrukcja żuchwy, przeszczepy autogenne, implanty stomatologiczne, analiza MES

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1. Introduction

Partial resection of the mandible becomes a necessary surgery in the case of extensive cancerous changes or severe traumatic lesions. The lack of bone continuity results in the move of mandibular parts upwards and paracentrically due to the action of stomatognathic system muscles. This causes significant defects, both functional (speaking and chewing problems) and aesthetic (face deformation). Therefore, reconstruction using bone graft must be performed [8].

The reconstruction of the mandible is an extremely difficult task, and despite the existence of many surgical techniques, none of them have been described as the perfect clinical method [11]. Slooffa's studies on the graft healing process enabled the identification of factors affecting its quality and duration time. These are: stabilization of the recipient's bone graft, a vast contact area between the graft and the bone tissue of the recipient, regular blood supply around the transplant and mechanical strength of the graft enabling load transmission [28].

One of the most important clinical problems is the size of the removed part of the mandible together with its location. The worst condition for the reconstruction of mandibular defects are caused by cavities in a part of the chin, because excision of a fragment with the mouth front part and muscles causes displacement of the other parts of the mandible [15]. Filling the cavity in this part involves the reconstruction of both the continuity and the curvature of a bone [20]. At the same time, reconstruction of the large fragments of mandible reduces the possibility for subsequent full rehabilitation of the stomatognathic system. Therefore, the aim of the restorative surgery should be rebuilding the prosthetic base and intraosseous dental implants introduced for subsequent full teeth restoration. Bone graft must ensure sufficient width and height for the introduced implants of length appropriate in order to maintain the designed prosthesis during functional loading for a long time [6, 21, 24].

In present-day maxillofacial surgery, as the treatment of choice, autogenous grafts from the iliac crest stabilized with titanium, reconstructive plates are predominantly used. In the case of reconstruction of the chin part, free tibia graft is mostly preferred due to the possible extensive osteotomies, which ensure accurate formation and curvature of the graft [20]. The most common types of implants for restoration are intraosseous, either rotationally-symmetric or cylindrical, or various threads that are screw-shaped, directly connected with a bone subjected to functional load [13].

FEM analysis of stresses and strains distribution in the mandible and around implants placed in it is an important issue in dental engineering. In most published papers, only models of small bone sections with implants placed in it are analyzed [1, 14, 18, 22, 23, 29–32, 34, 35]. It does not allow for the assessment of stresses and strains in the mandible after the surgical removal of the bone part. The authors of those papers tried to evaluate the stress in implants and compare the values of selected strength indicators in the mandible with teeth and introduced dental implants. There are also numerical simulations, in which the entire (not reconstructed) mandible with implants was analyzed [2, 3, 5, 7, 10, 19, 33] and also models, which analyzed only the reconstructed mandible with the bone graft [12, 26, 27]. The inspiration for the creation of this paper was the lack of simulations for simultaneous mandibular reconstruction and implant dentistry.

2. Aim of the work

The aim of this paper is to evaluate how the parameters of the embedded dental implants affect the distribution of the strain intensity in bone and graft. A model of the mandible with autogenous graft and dental implants introduced for teeth restoration is created. The authors try to evaluate the conditions for possible bone union on the mandible-graft border under physiological load in the area of front teeth based on selected strength parameters. FEM analysis is applied to determine the necessary conditions in order to begin the bone remodeling process. The aim is achieved based on analysis of strain intensity distribution in the bone and the von Mises stress distribution in the dental implants.

3. Material and method

The numerical model of the mandible with the graft is created using FEMAP software and based on the clinical case in which the osteotomy lines were carried out in the region of the mental foramen, between the canine and the first molar. The finite element model of the mandible is created based on a specimen obtained post mortem. The mandible geometry is modeled with points which coordinates are measured in a coordinate system. The asymmetry of the removed bone is taken into account. Four cases of the mandible continuity restoration with three various autogenous grafts, as a block of bone taken from fibula, iliac crest and rib, are considered. The following cases relate to various dimensions of the implant (Tab. 1). A 13-hole 2,4 Synthes reconstruction plate and 10 UniLock screws are modeled.

Callus, formed in the process of healing, is modeled as a body with a thickness of 0.1 mm. Four titanium implants are introduced into the graft. The created spatial configuration corresponds to the restored incisors – ones and twos (31, 32, 41, 42[1]). The designed implant models are based on the shape and dimensions of a typical dental implant and simplified to truncated cones as shown in Fig. 1. Additionally, at the top of each implant, a ceramic element is created for a prosthetic superstructure. Fully bonded interfaces are assumed between the bone and implant, simulating complete osseointegration. The dimensions of the dental implant are given in Table 1.

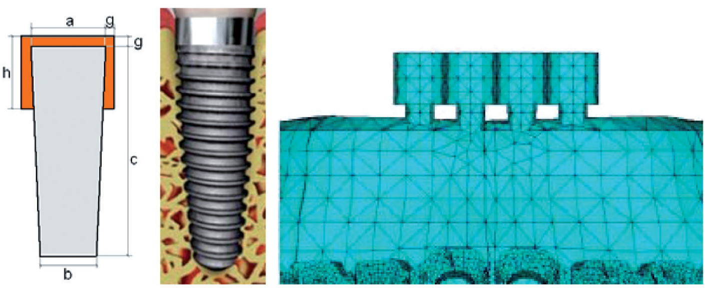

Fig. 1. Shape and dimensions of the implant and its FE model

[1] Viohl's dental notation.

The model is meshed using 10-node solid tetrahedral elements in Ansys. The final model, depending on the case, comprises approximately 64 000 elements (DOF 120 000).

Table 1

Dimensions of the implants

Case	Dimensions [mm]				
	a	b	c	g	h
I	3.0	2.5	18	1	5
II			13		
III	4.5	4.0	18		
IV			13		

The load scheme assuming the muscles action is adopted as the closest to the physiological conditions of stomatognathic system work. The load scheme is modeled on the following assumptions:

– the actions of four muscles are considered, i.e., the temporal (T), masseter (M), medial (MP) and lateral pterygoid (LP) muscles (Fig. 2);
– forces are applied at the site of muscle insertion, consistently with the size of the respective insertion area; directions of forces are based on literature data [27];
– the load model includes typical, physiological bite forces;
– simplified temporomandibular joint, composed of the articular disc and temporal bone fragment, is modeled.

As a result of the adopted scheme load (biting on the front teeth), the applied constraints involve the blockage of translational movements in all directions. The constraints are applied on the upper surfaces of the modeled, simplified temporomandibular joints and titanium implants placed into the bone graft (Fig. 2).

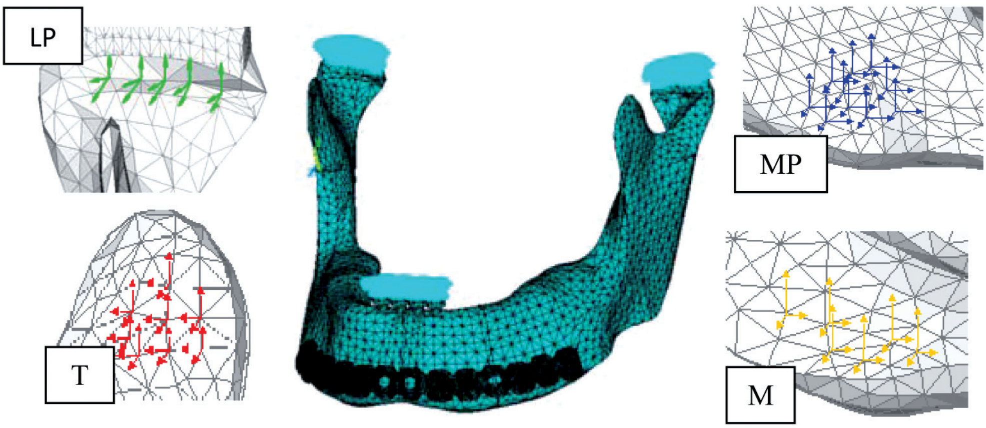

Fig. 2. The model of the mandible with forces and constraints applied

The total value of force applied by the muscles is assumed as 100 N, which is in the range adopted by other authors: 50÷150 N [2, 3, 19, 27]. The use of different bone materials is modeled by changing the material constants as shown in Tab. 2. The mandible is assumed to be a homogenous, isotropic and linearly elastic material. Such an approximation is based on the fact that strain-stress analysis not only takes into account the bone structure, but also the mandible-plate reconstruction-dental implant scheme (the latter two ar isotropic materials). Also, in the case of the mandible, the orthotropy ratio is smaller than that for the long bones, which approaches mandible structure to isotropic material [25]. The trabecular structure of the bone is not included. This approach is motivated by the fact that the mandible is composed mostly of a cortical structure, which, according to literature [9], may account for up to 79–89% of the entire bone. It is assumed that the bone strength corresponds to the compact bone tissue (cortical bone). Hence, it is assumed that the model of the mandible is made entirely of isotropic material (cortical bone), and the resulting stress distribution depends on the geometry of the mandible. At the same time, used for further analysis, H-M-H hypothesis refers to isotropic materials. The simulations are performed for the Young modulus of the callus equal to 200 MPa, which corresponds to the final stage of the bone healing process (after approx. 6–8 weeks). Changes in the tissue of the mandible, graft, reconstructive plate and implants induced by physiological load are evaluated on the basis of selected strength parameters, i.e. strain intensity and equivalent stress.

Table 2

Material constants used in analyses

Material	Young modulus E [MPa]	Poisson ratio ν	References
mandible	18000	0.32	[17]
graft			[16]
iliac crest	8000	0.35	[16]
rib	11500	0.30	[16]
fibula	21100	0.30	[16]
callus	200	0.40	[17]
articular disc	50	0.45	[5]
temporal bone	15000	0.32	[5]
reconstruction plate (Ti-6Al-7Nb)	108000	0.30	[25]
screws (Ti-6Al-7Nb)	108000	0.30	[25]
dental implants (Ti-6Al-4V)	110000	0.30	[25]
ceramic (ZrO_2)	210000	0.19	[25]

4. Results

The results of the analyses are presented in the form of a bar graph and stress/strain maps. The exertion of the reconstruction plate is described by the values of reduced stress calculated according to the Huber-Mises-Hencky hypothesis σ_{HMH} MPa. Stress analysis enables the assessment of the relationship between the occlusal load and stress distribution in the implants. The exertion of mandibular hard tissues and autogenous grafts is determined based on the values of the strain intensity ε_{int}. Changes in strain values are the most important factors, which stimulate adaptive responses of the bone tissue, associated with mechanical deformation field [25]. The interaction between the implant and the graft is evaluated. The implant thread is not modelled because of the lack of the trabecular structure. Also, the analysis is carried out for complete osseointegration when the movement between the bone and the implant can be neglected. The authors try to determine the extent to which physiological load affects the response of bone tissue at various geometrical parameters of implants. The more detailed model of the thread would be significant if the process of the osseointegration was the main aim of the analysis. Here, it is assumed that the osseointegration is completed.

The analyses are carried out for left (LOL) and right (ROL) osteotomy lines between the mandible and graft and in the region of titanium implants' contact with the transplant because these are the areas where processes of failure or overloading of bone tissue are observed.

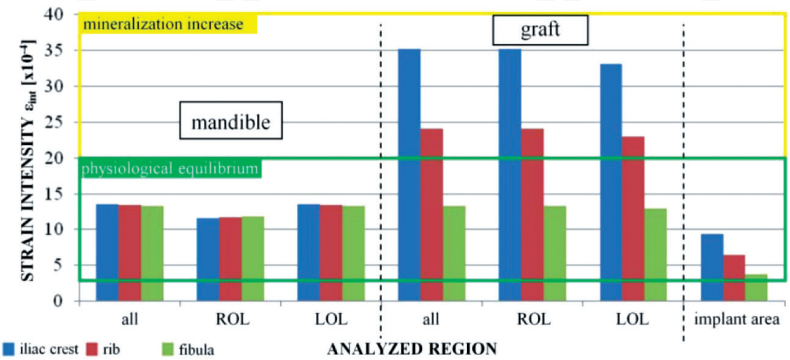

Fig. 3. The maximum value of the strain intensity in the mandible, graft and around implants depending on the type of autogenous graft in the case I

In all four cases, both for the entire mandible and on the border with the graft (left and right osteotomy line), the maximum strain intensity values in the mandible are observed in the range of physiological equilibrium ($2 \div 20 \times 10^{-4}$). Depending on the particular case (Table 1) and the material used for reconstruction, the ε_{int} differences are approx. 8%. For case I, the region of highest exertion of the mandible is located in the left osteotomy line (Fig. 3), while in other cases, it is met in the area of the right line osteotomy. However, the values of the strain intensity remain on a similar level in all regions. The strain intensity values are within the range of physiological equilibrium only in the case of using transplant material obtained from the fibula. For the other bone materials, ε_{int} reaches the values corresponding to the mineralization increase ($20 \div 40 \times 10^{-4}$). The region of the greatest exertion in the graft is located in the area near the right osteotomy line in case I, independently of the bone graft material, and in cases II, III and IV in which the material obtained from the fibula is used for reconstruction. In contrary, in other cases, the maximum value of ε_{int} is located in the region of the hole closer to the LOL, where the fixing screw is placed (Fig. 4).

The region of the greatest exertion in the graft-implant area is located near tooth 31 or 41, regardless of the geometry of the used implant and graft material. Thus, these parameters have no effect on the ε_{int} maximum values and the exertion region in the bone.

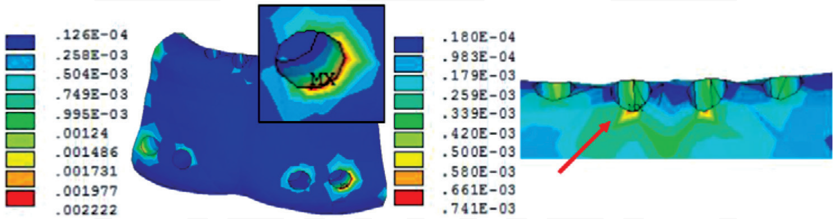

Fig. 4. ε_{int} distribution in graft tissue and at the bone-implant border for the case II with a bone material obtained from the rib

The stress concentration in the reconstruction plate is located near the border between the mandible and graft (LLO) at the point of contact with the screw. In the cases when implants with top diameter of 3.0 mm are used, the region of greatest exertion in the reconstruction plate is located on the side of the mandible (Fig. 5), whereas for implants with top diameter of 4.5 mm – on the side of the graft. The maximum values of the equivalent stress are in the range of 138–175.8 MPa. Such values remain below the yield strength for the titanium alloy and do not cause destruction of the plate.

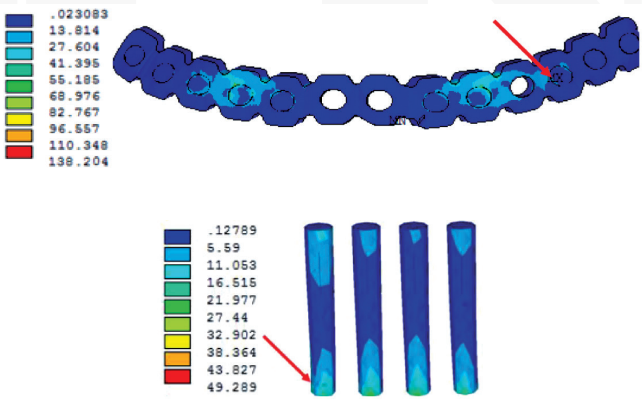

Fig. 5. Equivalent stress distribution in the reconstruction plate and dental implants in case I with iliac crest graft used for transplantation (front view)

The maximum stress value in implants occurs in the same place (area of the tooth 42 in the lower part of the tongue side) for all cases, regardless of the geometry of the implant and the type of bone material used for transplantation. Introduction of implants with top diameter of 4.5 mm (case III and IV) results in an almost double increase of the maximum stress value in the implant in relation to case I and II (Tab. 3). Although, it does not affect the qualitative distribution of the equivalent stress.

Table 3

The maximum equivalent stress σ_{HMH} in reconstruction plates and implants depending on the autogenous graft type

	Case I	Case II	Case III	Case IV
	Reconstruction plate – maximum equivalent stress σ_{HMH} [MPa]			
iliac crest	138.2	138.8	148.8	153.7
fibula	142.1	138.0	170.0	175.8
rib	141.2	138.7	144.3	138.1
	Dental implants – maximum equivalent stress σ_{HMH} [MPa]			
iliac crest	49.3	40.2	81.2	104.4
fibula	48.3	38.2	72.1	92.3
rib	45.5	33.9	74.7	83.6

5. Conclusions

Biomechanical analysis of the mandible-graft-reconstructive plate allows for the assessment of the treatment in terms of the proper work of the reconstructed stomatognathic system. Based on numerical simulations, it is possible to determine the necessary conditions for the initiation of the healing process and to analyze the mandible remodeling during healing. The usage of free bone grafts allows dental implants' introduction for the purpose of prosthetic rehabilitation. It enables early dental implants' partial loading, which can cause perigraft bone structures targeted layering.

The analysis showed that the type of bone material used for the reconstruction has an impact on the strain observed at the border of the mandible-graft and in the area between dental implants and the graft. The highest values of the strain intensity (ε_{int}) are observed for material taken from the iliac crest.

The geometrical dimensions of the implants have no significant impact on the value of ε_{int} in the mandible – with a load of 100 N, it remains in the range of physiological equilibrium. According to the hypothesis of a mechanical stimulator of bone tissue remodeling process, the range of values for a physiological equilibrium is 2÷20 [$\times 10^{-4}$] [25].

Increasing the implants' diameter does not significantly affect the equivalent stress distribution in the implant, although it causes almost double increase of its maximum value, but does not exceed the yield strength value for titanium alloy. The differences in the materials used as graft and implant dimensions have no significant impact on the value of the maximum stress in the reconstruction plate in cases I and II (the difference does not exceed 2%). In cases III and IV, where fibula graft is used for reconstruction, the obtained equivalent stress σ_{HMH} values are higher by approx. 12% for longer dental implants (18 mm) and 21% for the shorter (13 mm), compared to other graft materials. However, according to other authors, fibula graft creates favorable conditions for the maintenance of intraosseous dental implants and subsequent prosthetic rehabilitation based on implants' introduction [24].

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