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COMPARATIVE EVALUATION OF THE MECHANICAL PROPERTIES OF RESORBABLE AND TITANIUM MINIPLATES USED FOR FIXATION OF MANDIBULAR CONDYLE FRACTURES

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In this paper, comparative evaluation of the mechanical properties of resorbable and titanium miniplates, which are used for the fixation of the mandibular condyle fractures, was carried out using finite element analysis (FEA). To do so, first two-dimensional (2D) computed tomography (CT) images of mandibles recorded from 10 adult patients were converted into three-dimensional (3D) solid body models. Then these models were transferred to the finite element software. In the finite element stage of the study, a condyle fracture was created onto the mandible and double-titanium and double-resorbable miniplates were separately fixed to the mandible surface such that the fractured sites to be firmly attached. Stress distribution over the plates and interfragmentary displacements between adjacent surfaces, which stem from the clenching force applying to the mandible, were calculated using FEA. It was observed from the results that maximum tensile stresses occurred in the titanium miniplates were significantly higher than those obtained from resorbable miniplates ($p < 0.01$). Higher maximum displacements between fractured surfaces were observed in the case of resorbable plate systems ($p < 0.01$). Maximum stress and displacement values obtained from both titanium and resorbable plate systems were under clinically acceptable limits. According to results, resorbable plates showed a similar reliability with titanium miniplates in terms of withstanding various stress and strain deformations.

Keywords: Mandibular condyle fracture; titanium miniplate; resorbable miniplate; finite element analysis (FEA).

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1. Introduction

The condylar process is one of the most frequently fractured regions after traumatic injuries involving the mandible and its treatment is technically challenging.[1] There are two main surgical treatment methods as conventional intermaxillary fixation and rigid internal fixation.[2] Rigid internal fixation, which is providing functional stability during healing process, is now accepted as routine procedure for surgical management of mandible fractures.[3,4] It is well-known that ideal reduction is the main point of the healing process and the ideal rigid fixation hardware must provide strong and rigid reduction.[5]

There are many different types of rigid fixation hardware systems used for mandibular condyle fractures and each of these systems has specific pros and cons.[6] The miniplates used for fixation of the mandibular fractures must (i) be biocompatible, (ii) withstand various stress and strain deformations due to tensile forces, (iii) have to be malleable for easy adaptation to bone surface and, (iv) have minimal dimensions to be covered by mucosa. Titanium miniplates and screws have been widely used for rigid fixation of the mandibular condyle fractures.[7,8] The main drawback of these metallic fixations is to require a second surgery to be removed from the body. The development of resorbable materials has proposed an effective remedy for this problem.[9] However, the reliability of the resorbable materials in fixation of different jaw sites after fractures remains controversial.[10]

In this paper, biomechanical properties of miniplates used for mandibular condylar neck fractures, fabricated from resorbable and titanium materials, were comparatively evaluated by using finite element analysis (FEA).

2. Materials and Method

2.1. *Data collection and study design*

Computed tomography (CT) images of mandibles from 10 adult patients, which were recorded previously for different reasons rather than a pathology effecting ramus and condyle, with an axial thickness of 0.5 mm were used for the construction of three-dimensional (3D) mandible models. In order to observe the effect of topographic features of mandible on biomechanical behaviors, 10 different 3D models were used to obtain statistical results. Initially, mandibles were isolated from whole CT data and 3D computer models were reconstructed.[11] The cortical layer was designed all around the mandibles in 1 mm thickness. Then, diagonal fracture lines starting from mandibular notch and reaching to the posterior border of the ramus, completely separating the condyle and the vertical ramus, were simulated (Fig. 1). The fracture line was designed completely dislocated and boundary conditions were not implemented between fracture parts. Two four-hole isotropic and homogenous miniplates, which are made of titanium and resorbable (copolymer of L-lactide (17%), D-lactide (78.5%), and trimethylene carbonate (TMC) monomers (4.5%)) materials with 1 mm thickness, were designed. Double-titanium

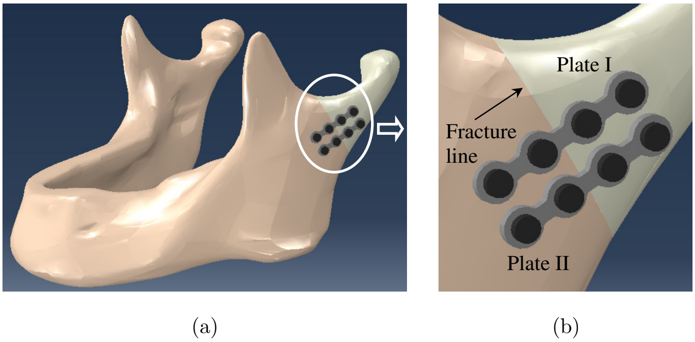

Fig. 1. (Color online) A typical representation of a mandible with miniplates which are used as fixators for healing of the mandibular condyle fracture. (a) General perspective view and (b) zoom-in view.

and double-resorbable miniplates were separately placed onto the appropriate positions between the fractured parts in 3D construction software (Fig. 1). Four isotropic and homogenous miniscrews, with 1.55 mm in diameter, were also designed and placed into the bone passing through the miniplate's screw holes. It was considered that the fixation of the screws to the bone is rigid and the functional forces were transferred from bone to the miniplate via screws completely. Anisotropic properties of mandible were negligible.

2.2. *FEA*

Since the spongious layer of bone does not provide meaningful stiffness and nearly all strength of the bone is compensated by the cortical layer, all mandibles were modeled as a shell, which consist of cortical bone layer with 1 mm thickness. Double-miniplate system, which has been well accepted as standard procedure in maxillofacial surgery,[7] were applied to fix the simulated mandibular condylar fracture. Hereafter, the miniplates, which were placed on the superior and inferior condyle neck, are referred to as Plates I and II, respectively (Fig. 1). All plates were assumed to have linearly elastic — isotropic behavior and their mechanical properties can be described by the Young's modulus and Poisson's ratio. The mechanical properties of the cortical bone, titanium and resorbable miniplates were given in Table A.1.

Global edge length of 0.75 mm and quadratic tetrahedral element type were assigned for the miniplate and screw meshing. For the cortical meshing, 1.5 mm global edge length and 3-node triangular shell element type were chosen. All 10 models had 46 560 elements and 28 959 nodes in average, thereby enabling the model has a high accuracy.

Each screw was determined to be bounded (no slip and clearance) with miniplates and cortical bone, which enables miniplates to be fixed firmly to the cortical bone. The bone surfaces between fracture lines were considered to be frictional.

A clenching force of 62.8 N, which is vertical to the occlusal plane of molar region at the same site of fracture line, were applied for the simulation of the unilateral molar clenching forces and different pairs of parallel vectors were preferred for the realistic simulation of clenching movements.[12] The condylar heads were constrained to all translation movement and only allowed for rotational movement. For all cases, the load and analysis were assumed static.

3. Results

von-Mises stress distribution and interfragmentary displacements were comparatively evaluated according to the results obtained from FEA.

Maximum stresses over the miniplates and maximum displacements between the fracture surfaces for each mandible were given in Table 1. Maximum stress values observed in the titanium miniplates are higher than those in the resorbable miniplates for all cases. Also, maximum displacement values occurred in the resorbable plate system are higher than those in the titanium plate system for all cases. To observe whether the stress and displacement differences observed between titanium and resorbable plate systems are statistically significant, one way ANOVA was employed. The differences were evaluated at a level of significance of 0.01.

It was observed that the maximum stress and displacement differences between titanium and resorbable plate systems were statistically significant (Fig. 2). Averages of maximum stresses were calculated as 36.5 MPa and 8.63 MPa for titanium and resorbable fixators, respectively (Fig. 2(a)). Averages of maximum displacements were calculated as 0.66 μm and 2.49 μm for titanium and resorbable materials, respectively (Fig. 2(b)).

Table 1. Maximum stress and displacement values obtained from double-titanium and double-resorbable miniplate systems.

	Maximum stress value in the plates (MPa)				Maximum displacement between fractured surfaces (μm)	
Number of mandible model	Titanium plate I	Titanium plate II	Resorbable plate I	Resorbable plate II	Titanium plate system	Resorbable plate system
Model 1	37	20	8	5	0.046	0.458
Model 2	36	30	11	7	0.398	1.750
Model 3	33	33	6	6	0.545	1.690
Model 4	33	38	7	8	0.528	1.440
Model 5	42	14	12	6	0.541	2.150
Model 6	33	44	2,8	10	0.600	3.040
Model 7	45	45	9	10	0.762	3.870
Model 8	28	13	7	2,3	0.333	0.973
Model 9	40	20	11	6	2.700	5.880
Model 10	38	55	4	26	0.226	3.650

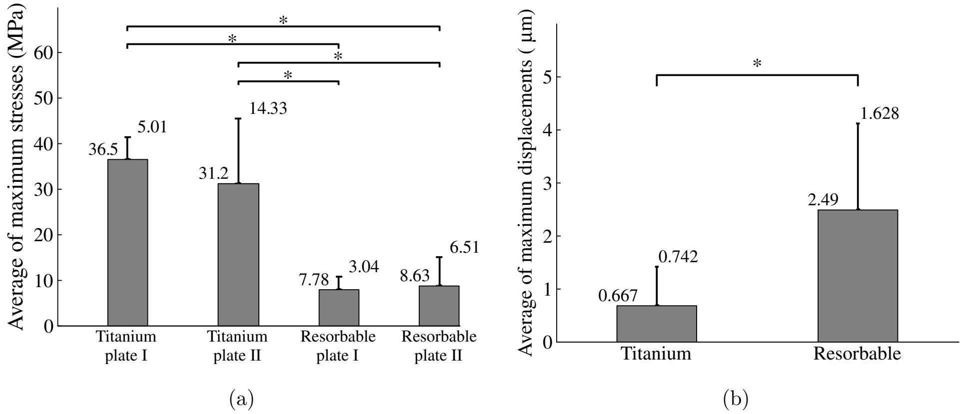

Fig. 2. Average (± standard deviation) values of (a) maximum stresses over titanium and resorbable plates and (b) displacements between fractured surfaces for all 10 cases. $^{*}p < 0.01$.

4. Discussion

Mandibular condyle fractures are one of the most common fracture types of the maxillofacial region[13] and the ideal treatment protocol for condylar fractures are still controversial.[8] The conventional method, i.e., the intermaxillary fixation and functional treatment combination, is still used.[14] On the other hand, rigid fixation by open reduction has become popular thanks to the developments in the field of osteosynthesis technologies.[15]

Intermaxillary fixation is not a comfortable choice and has side effects mostly on periodontal tissues. Also it causes function loss during healing period. By the open reduction, patients can return to function earlier than intermaxillary fixation significantly.[16] Otherwise, need to surgical approach and, in some cases, second surgery to remove fixation hardware are the basic disadvantages of open reduction.

The utilization of resorbable osteosynthesis systems is useful for the elimination of second surgery to remove rigid fixation hardware, but we are not still sure the mechanical qualifications of this kind of resorbable rigid fixation materials.[17] In addition, resorbable rigid fixation hardware is more expensive than the non-resorbables and they are also thicker to compensate the mechanical inability.

The utilization of double four-hole titanium miniplates and eight miniscrews is the material of choice for the rigid fixation of mandibular condyle fractures by open reduction.[18] In this research, biomechanical properties of resorbable fixation hardware were compared with the conventional titanium miniplates. For this aim, maximum von-Mises stress distribution on the miniplates and displacement between fractured surfaces during loading were evaluated.

Advantages of the two-titanium miniplate placement system for the treatment of mandibular condylar fractures by open reduction were experienced in clinical and in *in vitro* studies and this method has become a standard protocol.[7] For this reason, in this paper, fixation by double four-hole titanium miniplates were considered as control group and compared with fixation by double-resorbable four-hole miniplates.

The mechanical characteristics of resorbable material are directly related to the Young's modulus and the Poison's ratio. Therefore, to evaluate the material-based differences between titanium and resorbable miniplates, all parameters other than Young's modulus and Poisson's ratio, which are affecting mechanical behavior of fixations, were kept stable.

Considering the maximum von-Mises stress results, statistically significant difference was found between resorbable and titanium materials. All maximum stresses occurred over both material types stayed clearly below the plastic deformation limits of the materials (see Table A.1 for the yield stress values of materials). Although the titanium is more resistant to the tensile stress than the resorbable material, both titanium and resorbable materials are suitable for the rigid fixation of the mandibular condyle fractures.

Because of its more flexible characteristics, displacements between fracture lines were found significantly higher in resorbable material fixation system than those in the titanium system. On the other hand, both displacement values of titanium and resorbable materials were below the acceptable gap healing values.[19]

Several limitations of the study need to be mentioned. Because the cancellous bone structure of mandible does not provide meaningful stiffness when comparing with the cortical bone, all mandibles were modeled as homogeneous shell structures, namely the mandible model was consisted of only cortical bone. By doing so, the analysis was enabled to be less susceptible to model related failures. In addition, it was assumed that the thickness of the cortical layer is 1 mm, whereas it is well-known that the thickness of cortical bone differs around the mandible.[20] The boundary conditions subjected to the temporomandibular joint (TMJ) allowed to make only rotational movement. However, the TMJ has two distinct movements i.e., rotation and translation during mandibular opening and closing.[21] In the model, unlike the real cases, the applied chewing force was assumed to be constant and applied only in vertical direction. In next step of this study, it is planed to eliminate some of these limitations, thereby improving the mandible model such that simulates the human mandible in a more realistic way.

5. Conclusion

The actual forces being applied to the condyle have not yet been completely identified and scientists are still searching the ideal rigid fixation material to deal with functional forces. Today's biomaterial technology brings us titanium as a biocompatible, mechanically resistant, cheap and reliable material, but not as effective as it is expected. Due to the necessity of removal surgery for titanium plate, it can be concluded that resorbable miniplates can be a convenient alternative to titanium material for the rigid fixation of mandibular condyle fractures.

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Appendix A.

A.1. *Model parameters*

Table A.1. Mechanical properties of the cortical bone and miniplates evaluated in this study.

	Young's modulus (MPa)	Poisson's ratio	Yield strength (MPa)
Cortical bone	15 000	0.33	—
Titanium miniplate	115 000	0.34	462
Resorbable miniplate	3150	0.46	72