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Mandibular reconstruction – biomechanical strength analysis (FEM) based on a retrospective clinical analysis of selected patients

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Restoration of mandible discontinuity defects continues as a challenge for maxillofacial surgeons. Despite the development of algorithms for reconstruction plates fixation and autogenous grafting techniques, complications are still encountered including screw loosening, bone resorption or delayed/incomplete union.

The aim of the study was to analyze the possibility of obtaining bone union in the aspect of biomechanical conditions of two mandible reconstructions using an autogenous iliac crest bone graft stabilized with a reconstruction plate, and to attempt to predict patient outcomes based on strength parameters obtained by the finite element analysis.

The authors of the present paper were trying to determine to what extent the reconstruction model and changes occurring in hard tissues of the bone and autogenous graft (simulated by changes in material properties) might help predict individual patient courses. The effort of reconstruction plates was defined using the values of the von Mises stress (σ_{HMH}) while the effort of bones was determined based on the values of strain intensity $\varepsilon_{\mathrm{int}}$. The results of the above mentioned simulations are presented in the form of bar graphs and strain/stress distribution maps. Our strength analyses indicate that uncomplicated healing of grafts fixed with reconstruction plates requires that the initial loading of the stomatognatic system should not result in strain intensity exceeding 20–40 [$\times 10^{-4}$]. This range of strain intensity evokes an increase in the mineral phase. The state of nonunion between the mandibular bone and the graft might result from prolonged periods of insufficient loading of the mandible during treatment.

Key words: *bone grafts, mandibular reconstruction, finite element method (FEM), reconstruction plates, bone healing*

1. Introduction

Better technologies and strategies are needed for reconstruction of large facial defects in order to not only restore facial contour but also function (for functional and aesthetic restoration).

A large variety of oncological, traumatic and inflammatory pathologies of the face, which can cause bone discontinuity both as a result of the disease process and treatment are described in related literature [1]–[4]. The consequences include obstruction of air passages, restriction of food intake, mucus stasis, speech disturbances and facial disfigurement. Therefore, each and every mandible discontinuity should be restored. Autogenous bone grafts stabilized with titanium reconstruction plates are the treatment of choice. Reconstruction plate fixation schemes are, of course, demonstrated by plate manufacturers and company representatives. Instructions are provided regarding plate fixation which permits the optimum healing; this involves appropriate plate contouring to the surface of the bone, insertion of the right number of screws in each bone fragment, and

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plate positioning [2], [3], [5], [6]. However, the wide diversity of clinical cases, intraoperative findings, surgeon's experience and, last but not least, highly individual course of the healing process frequently hinder the therapeutic efforts of maxillofacial surgeons. Thus, a common algorithm should be developed to reduce complication rates.

The purpose of the present study was to perform a biomechanical assessment of the bone healing process using a numerical analysis by the finite element method (FEM). Such calculations, based on some selected strength parameters, allow objective evaluation of changes which occur within the bone/graft interface and in implanted elements.

A biomechanical analysis of a system composed of the mandible, graft and reconstruction plate facilitates the assessment of whether, and to what extent, the function of the stomatognatic system has actually been restored; thus, treatment effectiveness can also be determined. Numerical simulations enable researchers to define the optimum surgical fixation method, compare the efficiency of various reconstructions or analyse mandibular bone remodeling during healing.

Numerical simulations are highly reproducible and, additionally, less costly and more effective compared to clinical and laboratory investigations. They also allow analysis of various cases taking into consideration the object's geometrical variables, material constants and boundary conditions.

The aim of the study was to analyze the possibility of obtaining bone union in the aspect of biomechanical conditions of two mandible reconstructions using an autogenous iliac crest bone graft stabilized with a reconstruction plate, and to attempt to predict patient outcomes based on strength parameters obtained by the finite element analysis.

2. Materials and methods

In the years 2005 through 2011, four patients underwent mandibular reconstruction in the Department of Cranio-Maxillofacial and Dental Surgery, Medical University of Silesia, Katowice. The reconstructions were performed using an autogenous bone graft and 2.4 mm Synthes titanium reconstruction plates. Two of these were selected for strength analysis by the finite element method (FEM).

Patient 1 (uncomplicated healing during a three-year observation period): a 46-year-old female patient after mandibular body resection due to ameloblastoma and mandibular reconstruction using full-thickness iliac crest bone graft fixed with a contoured 17-hole Synthes titanium reconstruction plate (2.4 mm) and 10 UniLock screws: 3 screws were placed in the distal mandibular stump, 5 in the graft and 2 in the mesial mandibular stump. The plate was carefully contoured to the surface of the bone and placed closely to the lower mandibular margin so that it would be sufficiently covered by soft tissues (Fig. 1). The patient was on a dental soft diet for 6 weeks following the reconstruction, and then gradually advanced to rehabilitation of masticatory function through dental restorations. The surgery resulted in mandibular contour reconstruction; facial symmetry and aesthetics as well as basic masticatory function and bite force were restored (Fig. 2a, b).

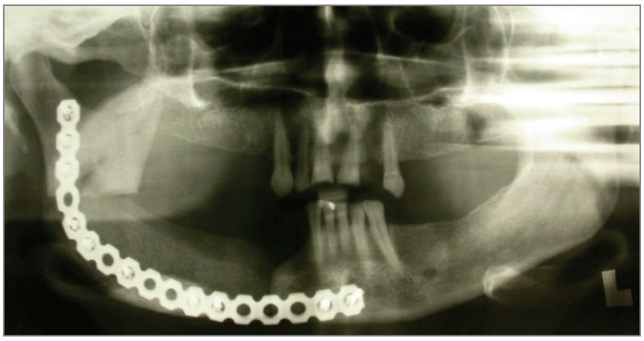

Fig. 1. Patient 1: Panoramic radiograph following mandibular body resection and reconstruction using autogenous full-thickness iliac crest bone graft stabilised with a 2.4 mm titanium reconstruction plate

Patient 2 (delayed union, prolonged healing period): a 42-year-old male patient after several unsuccessful attempts of comminuted mandibular fracture reduction and resultant pseudoarthrosis. A partial thickness defect of 1 cm in length was filled with an autogenous graft of cancellous iliac crest bone and stabilized using a 7-hole Synthes titanium reconstruction plate (2.4 mm) with 2 UniLock screws in each mandibular stump. The plate connecting both stumps ran obliquely and upwards on the outer surface of the mandible towards the mandibular angle (Fig. 3a, b, c). The healing period was markedly prolonged and c complicated by bone fragments mobility and facial asymmetry. Therefore, the position of the mandible relative to the maxilla was secured by interarch fixation wires for 8 weeks following surgery. Ultimately, over 2 years after the procedure, bone union occurred and normal dental occlusion as well as masticatory function and bite force were restored (Fig. 4a, b).

Fig. 2. Patient 1: (a) photograph of the patient's face; (b) intraoral image 2 years after reconstruction

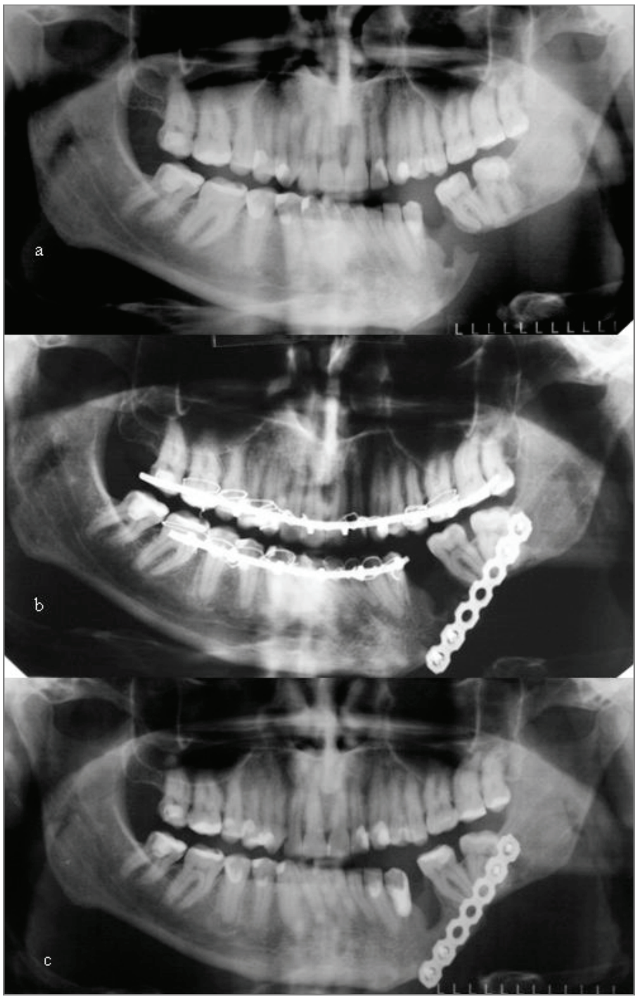

Fig. 3. Patient 2: Panoramic radiographs:
(a) prior to reconstruction; notice the pseudoarthrosis in the left molar region of the mandible with a 1 cm partial thickness defect (arrow); (b) after mandibular reconstruction with autogenous graft of cancellous iliac crest bone stabilised with a 2.4 mm titanium reconstruction plate; (c) 2 years and 4 months after reconstruction (note normal trabecular architecture and bone remodeling at reconstruction site (arrow))

Numerical analysis of the cases under consideration was performed using (CAD) FEMAP®. Teeth were disregarded and alveolar processes 'replaced' by the mandibular osseous tissue. The coronoid process, pterygoid fovea, mental spine and masseteric tuberosity were also disregarded. The resultant numerical model of the mandible was assigned appropriate material constants, i.e., elasticity modulus E = 18000 [MPa] and Poisson's ratio $\nu = 0.32$. A simplified model of the temporomandibular joint consisted of the articular disc and articular surface of the temporal bone. Consistent with literature data [7], material constants of the articular model components were $E = 50$ [MPa] and $\nu = 0.45$, and $E = 15000$ [MPa] and $\nu = 0.32$, for the articular disc and temporal bone, respectively. An element was also taken into consideration corresponding to the biomechanical properties of anterior teeth periodontium. According to the preassumed load scheme, the system was constrained on the surface of the temporal bone and the periodontium-corresponding element.

The autogenous, iliac bone-harvested graft of Patient 1 was assigned material constants of E = 8000 MPa and ν = 0.35. Simulations concerned changes in callus mineralization between the initial phase of the healing process and ultimate bone union about 6 to 8 weeks following the procedure. Mineralization changes were simulated by changes in the elasticity modulus of a callus-modelling element for the values of 2, 5, 10, 25, 50, 75, 100, 125, 150, 175 and 200 MPa. Accepted values are approximate and are some extrapolation between the range of 2 MPa, in the early stages of healing and 200 MPa in the end, fed by Knets et al., because the literature does not provide a more detailed description of the changes in this value [8].

The second patient's mandibular defect was reconstructed using the cancellous bone of the iliac crest.

Devising a model of such material is extremely difficult due to the lack of the properties of solids. We ultimately decided to simulate mineralization changes as in the case of callus, i.e., by changes in the elasticity modulus. However, a greater range of values was taken into consideration, i.e., from 2 MPa (corresponding to bone status immediately following surgery) and up to 1000 MPa (final stage of treatment – complete bone mineralization). The models of bone fragments were designed to imitate the shape of bone stumps and their post-reconstruction status (Fig. 5a, b).

The models were exported to (FEM) ANSYS®, and subjected to loading. The load scheme was based on the following assumptions:

• the actions of four muscles were considered, i.e., of the temporal, masseter, medial and lateral pterygoid muscles;

• force application was at the site of muscle insertion and consistent with the size of the respective insertion area; percentages and average directions of the forces were based on literature [9]–[11];

• the load model included typical bite forces; the resultant (total) muscle force was assumed to have a value of 100 [N] [12]. Since loads are considerably lower at initial stages of the healing process, load change simulations depending on the healing phase were carried out for Patient 2 (load range: 10 N to 100 N).

Fig. 4. Patient 2: (a) photograph of the patient's face; (b) intraoral image 2 years after reconstruction

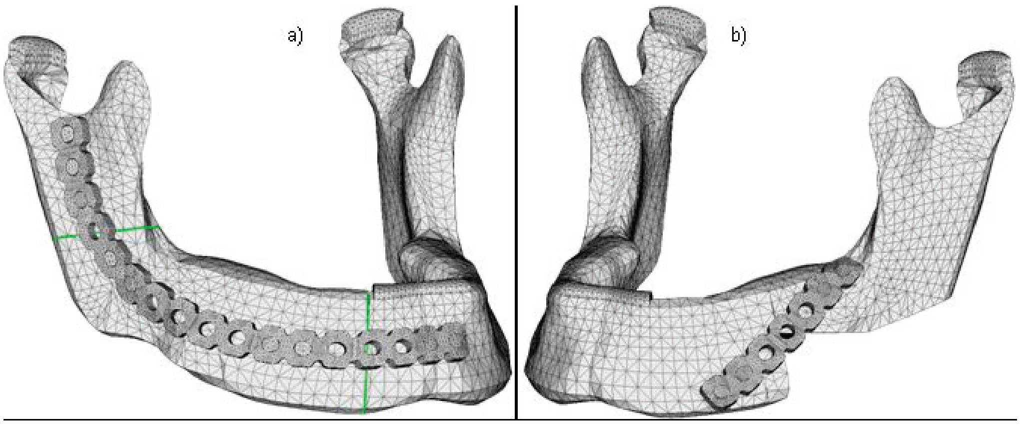

Fig. 5. Numerical models of the cases under analysis: (a) Patient 1; (b) Patient 2

Table 1. Strain intensities corresponding to bone tissue response to particular loads

Load characteristics	Strain intensity $\varepsilon[\times 10^{-4}]$	Bone tissue response
Destructive loads	>(150–200)	Destruction of bone tissue
Pathological overload	>40 (approx. 60)	Resorption, microfractures (plastic deformations)
Increased load but still within physiological range	20–40	Increase in bone mineralization
Physiological load	2–20	Bone tissue equilibrium
Underload	< 2	Decrease in bone mineralization

As accepted by the majority of authors [5], [10], [13]–[15], the effort of reconstruction plates was defined using the values of the von Mises stress (σ_{HMH}). The effort of mandibular hard tissues and autogenous grafts was determined based on the values of strain intensity ε_{int} (Table 1). Changes in strain distribution are the most important factor to stimulate adaptive responses of the bone tissue associated with mechanical deformation field [9]. The analyses were carried out for the proximal and distal osteotomy lines.

3. Results

Bar graphs (Fig. 6a, b) present changes in strain intensity ε_{int} associated with the degree of bone mineralization (i.e., healing phase) for a load of 100 N applied in the incisor area (Patient 1).

The values of strain intensity ε_{int} are greater in the proximal segment due to the assumed incisor load and the complex character of mandibular stresses. The mental and incisor areas, i.e., the proximal line area, are subject to bending and torsional stress whereas the area towards the mandibular angle is subject to bending stress only.

Strain intensity in the proximal area remains within the state of equilibrium and mineralization increase. Once callus elasticity modulus reaches the value of 5 MPa (initial healing phase), the system could be loaded, which probably increases the mineral phase and facilitates graft incorporation. As Patient 1 did not have maxillomandibular fixation, she was capable of mandibular abduction immediately following surgery. Afterwards she started to gradually load the system with dental soft diet which ultimately resulted in correct union.

The bar graph in Fig. 7 presents strain intensities for proximal and distal parts of cancellous bone graft

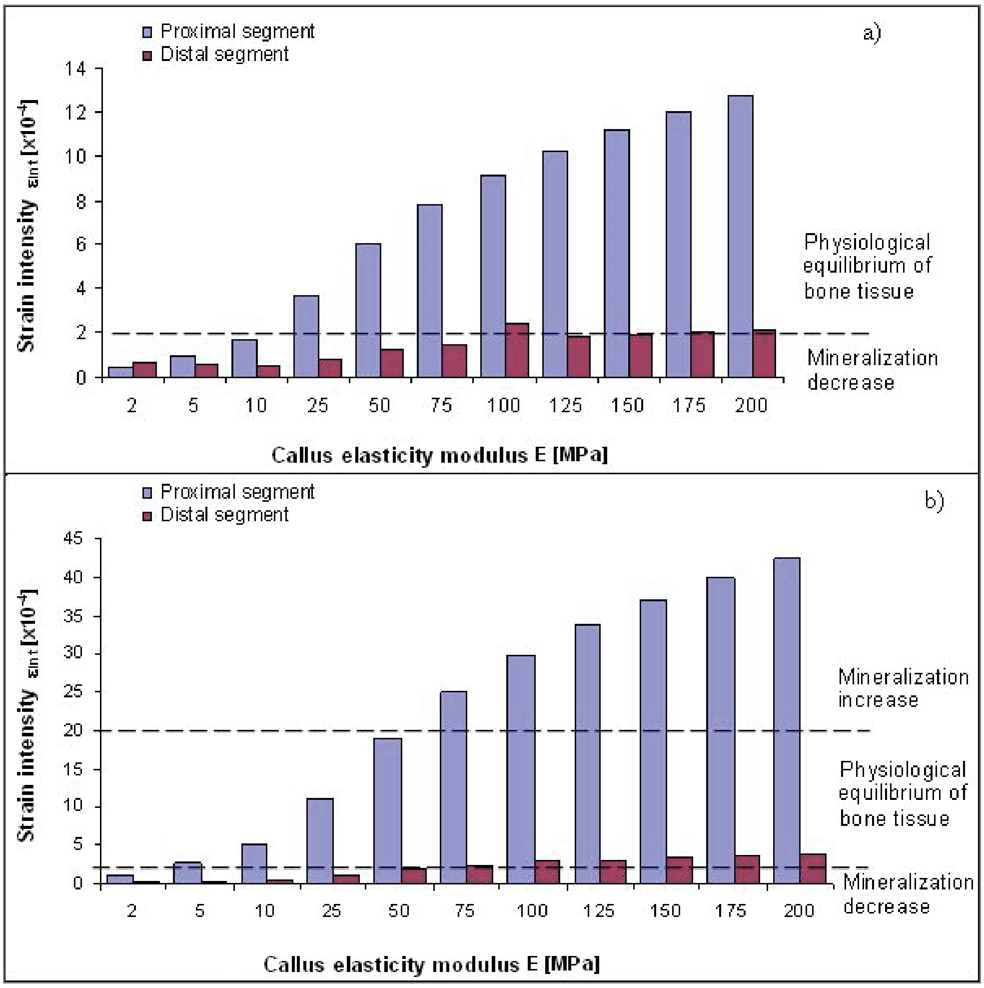

Fig. 6. Patient 1: (a) mandibular bone: strain intensity in the proximal and distal bone/graft interface; (b) iliac crest graft: strain intensity in the proximal and distal graft/bone interface

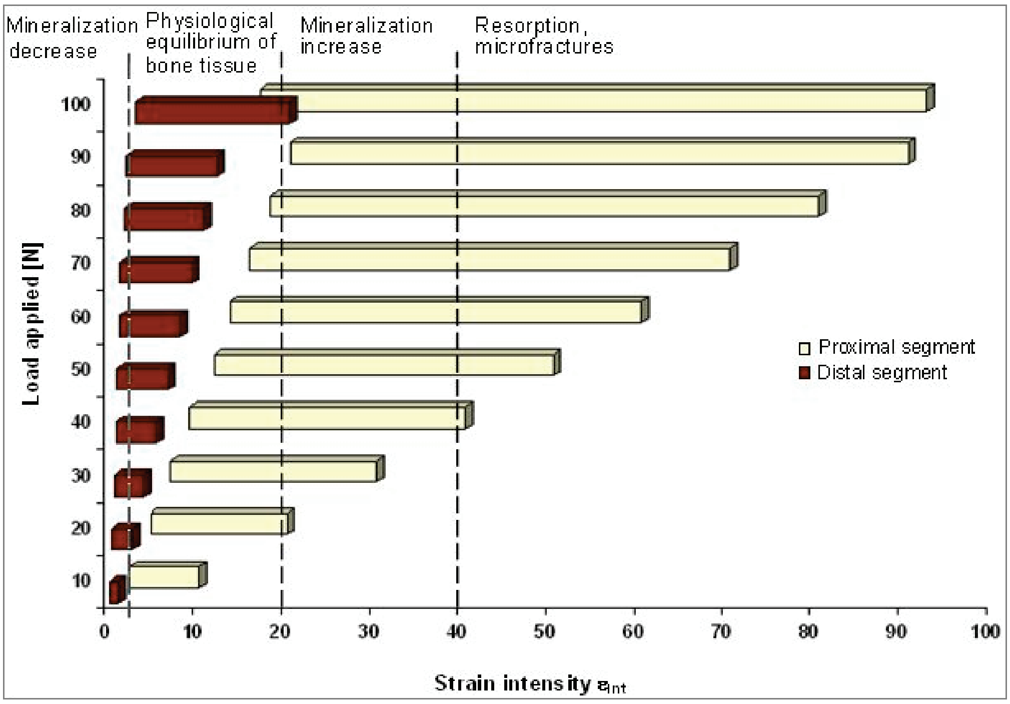

Fig. 7. Patient 2: The graft – mineralization stage dependent strain intensities at particular load values (proximal and distal areas)

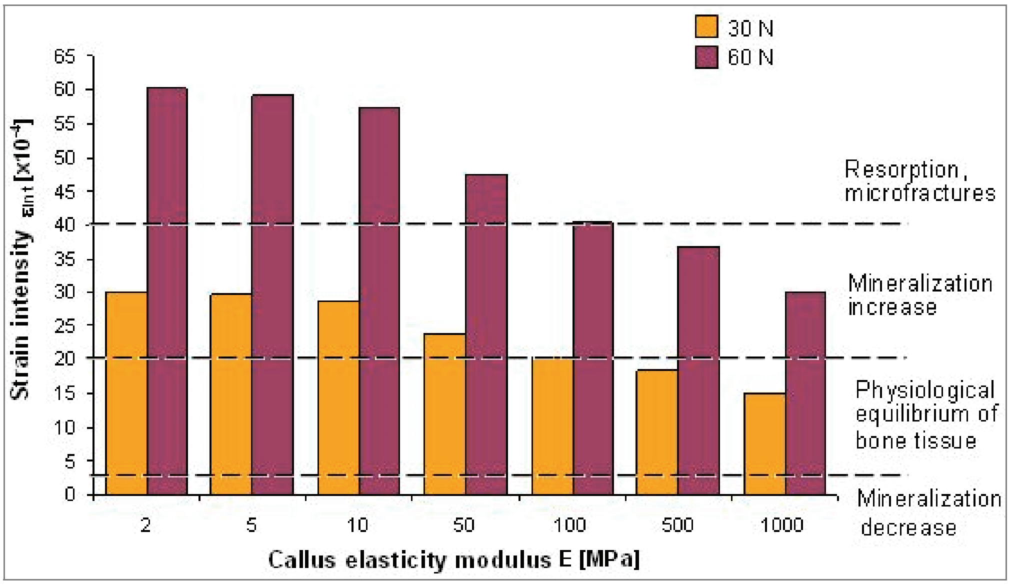

Fig. 8. Patient 2: Proximal graft area – strain intensity at the loads of 30 and 60 N

in Patient 2. The loads were between 10 N and 100 N depending on the degree of bone mineralization (i.e., healing phase).

Higher loads applied in the initial phases of healing resulted in strain intensities corresponding to pathological overloads that might lead to microfractures and resorption.

Following mandibular reconstruction, the force acting on the stomatognatic system will be below 100 N. However, it should not be too low. The graphs representing strain intensity changes associated with the changes in the total force values indicate that although lower loads evoke physiological bone tissue response in the proximal segment, the distal fragment reveals a decrease in bone mineralization

A load of approximately 30 N could be safely applied in a patient already in the initial phase of healing. Higher loads (e.g., 60 N) should be postponed until later time when the graft elasticity modulus increases to around 100 MPa (Fig. 8).

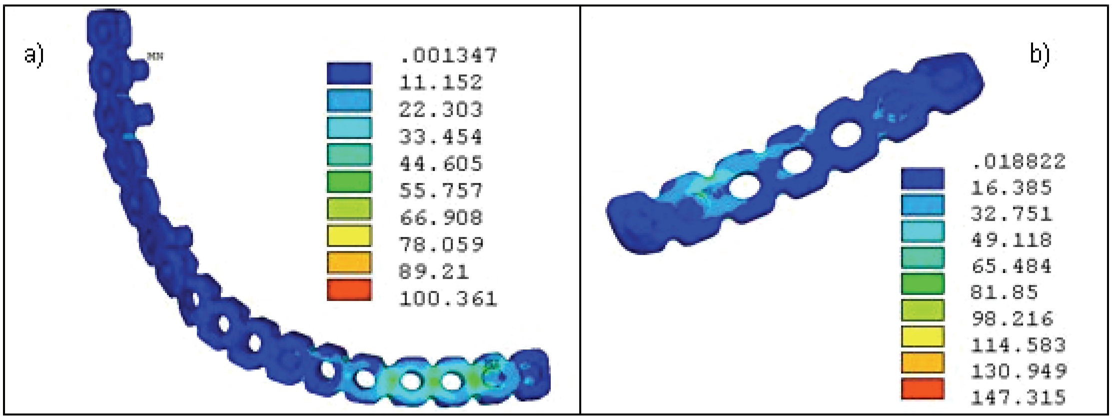

Fig. 9. The von Mises stress distribution σ_{HMH} [MPa] in reconstruction plates: (a) Patient 1; (b) Patient 2

Figure 9a, b presents the distributions of the von Mises stress in both reconstruction plates (Patients 1 and 2) under analysis. The distributions are similar, the greatest effort being observed in the proximal segment of the mandible–graft system.

4. Discussion

The authors of numerous reports published during the last few years have been trying to elucidate the biomechanical causes of mandibular reconstruction failures. The evaluation of reconstruction techniques including graft type and size as well as the type of stabilizing elements is carried out using computer-generated models, which are, of necessity, simplifications of real phenomena [5], [6], [14], [16]–[21]. The most significant thereof is treating the mandibular bone as an isotropic material, characterized by two material constants only, i.e., the elasticity modulus and Poisson's ratio [5], [16], [20]. The load of 100 N assigned in our investigations was used exclusively for simulation; its value is nevertheless consistent with that applied by other investigators [5], [14], [18], [21].

In maxillofacial surgery there are no clear-cut suggestions regarding the magnitude of mandibular hard tissues and graft effort. Therefore the effort of reconstruction plates was defined using the values of the von Mises stress while the effort of bones was determined based on the values of strain intensity ε_{int}, which is in accordance with available literature on the subject [5], [10], [13], [22].

Literature reports enumerate several mechanical stimulators of the bone tissue remodeling process. The most popular is the theory of functional adaptation of the bone to strain distribution. Changes in strain distribution are the most important factor to stimulate adaptive responses of the bone tissue associated with mechanical deformation field [20], [22].

Our analysis along with literature data seems to indicate that correct healing of reconstruction plate-fixed grafts depends on many factors. For example, the initial load on the stomatognatic system should not exceed magnitudes which induce strain intensity of 20–40 [$\times 10^{-4}$]. As long as strain intensity remains within this range, the mineral phase increases.

The biomechanical analysis suggests that Patient 2's mandibulomaxillary fixation should have been removed before week 8 after surgery. Prolonged placement could have resulted in stomatognatic system underloading, mineralization decrease and delayed healing. It should be emphasized that the check-up did not reveal any inflammatory complications that could also lead to graft bone resorption. Eight weeks following the procedure the patient started rehabilitation of masticatory function, which resulted in correct mineralization of union site and autogenous cancellous bone graft remodeling.

The evaluation of mandibular reconstruction is additionally hindered by the adaptation of the graft to the surrounding tissue. Graft incorporation is associated with both bone resorption and bone formation processes followed by bone remodeling. Correct union between the graft and mandibular bone is determined by the type of material used for reconstruction. Nagasao et al. observed that greater mastication-related stresses were transferred onto the reconstructed system in the case of a thinner bone being used for reconstruction (the fibula or rib) [18]. The widely preferred, most advantageous from the biomechanical point of view and therefore also used in our analysis, is the iliac crest. This bone also provides a larger contact surface with the recipient site [3], [19]. Tie et al. found that the von Mises stress distribution in mandibles repaired with iliac crest grafts was more similar to the normal mandible when compared with mandibles repaired using the fibula [19]. Unfortunately, the authors did not stabilize the grafts with reconstruction plates.

During the initial phase of the incorporation process, the graft is not stabilized relative to mandibular fragments. Numerous authors have emphasized the need for a reinforcing element that would take over a part of the functional load in the initial phase of treatment thus reducing the stress resulting from the masticatory forces and facilitating the union between mandibular bone and the graft [3], [16]. Mandibular plating allows more rapid resumption of oral functions and secures the graft to the mandibular segments even in the case of large sized grafts. It also allows better reconstruction of facial contours.

The results of Kimura et al. suggest that adequate fixation with a reconstruction plate requires avoidance of stress concentration in some parts of the plate and screws [23]. Uniform stress distribution, dependent on the site and size of bone defects, helps avoid complications including screw loosening, plate exposure or mastication-induced fractures [9], [23].

Our patients presented mandibular body defects (lateral defects). Patient 1 had an 8-cm defect reconstructed with a free cortico-cancellous graft. Patient 2 had a 1 cm partial thickness defect repaired with cancellous bone chips. In both patients, iliac crest bone was used for reconstruction. The difference between the graft and mandibular bone was simulated by changes in material constants.

There are discrepancies in literature reports regarding the number of screws to be used to secure the reconstruction plate on both mandibular stumps. Previously it was believed that longer plates and more screws increased stability and prevented complications such as titanium elements loosening and non-union [2], [3]. Mariani et al. argue that a reconstruction plate should be well aligned on the adjacent surface of the mandible and fixed with at least 3 screws on each side of the reconstructed segment [2].

Schuller-Götzburg et al. carried out biomechanical analyses on a three-dimensional finite element model of a mandible following resection and reconstruction using different methods. The aim of their investigations was to determine stress distribution differences between the bone, graft and reconstruction plate. They confirmed the stabilizing role of a reconstruction plate. However, they also remarked that such plates should not be too rigid so as not to delay graft union and incorporation [14].

Kimura et al. notice that, in the case of lateral defects, adding a third screw for fixation in each mandibular stump increases stress due to system overloading [23]. This can result in screw loosening and loss.

We did not observe screw loosening during a two-year observation period. Therefore we believe that the decision to secure the reconstruction plate with two UniLock screws was the right one.

The results of numerical simulations indicate that the most intense stress occurred around plate holes at the proximal graft/bone interface, which is consistent with other authors' observations [18]. Hard mandibular tissue necrosis develops relatively frequently in the area of graft/bone interface while inflammatory complications are observed in contact areas between plate/screws and tissues [13]. This is confirmed by strain intensity values associated with greater loading forces and bone effort at the site of screw insertion. Post-reconstruction patients should therefore be carefully monitored with special attention to radiological check-up of screw position.

Mandible plating allows the implementation of functional therapy immediately after surgery and thereby avoiding problems related to the predominance of bone resorption over bone formation. However, X-rays still reveal predominance of bone formation in the proximal end of the graft compared to its distal part [24]. Patient 1 also had higher strain intensities at the proximal graft/bone interface.

Our analyses concerned two extreme cases and techniques of reconstruction plate placement, size, position relative to the lower margin of mandibular body, method and duration of mandibular fixation. Also, although harvested from the hip bone, the two grafts had different tissue composition. The use of numerical analysis can pre-assess the extent to which advanced technology allows satisfactory long term outcome of reconstruction and restore biomechanical function of the mandible reconstructed.

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