Three-Dimensional Finite Element Analysis of Mechanical Stress in Symphyseal Fractured Human Mandible Reduced With Miniplates During Mastication

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Purpose: In this study we tried to analyze the stress distribution in a symphyseal fractured human mandible reduced by 2 different methods—reduction with 1 miniplate or with 2 miniplates—by using finite element (FE) analysis, and then compared the results with an intact mandible.

Materials and Methods: Three-dimensional FE models of an intact mandible and symphyseal fractured mandibles reduced by 2 fixation methods were developed to analyze mandibular stress distribution and bite forces under 2 basic loading conditions, namely, clenching in the intercuspal position and left unilateral molar clenching. Groups of parallel vectors were used to simulate 9 pairs of masticatory muscles involved in the 2 static biting tasks.

Results: Stress distributions in reduced mandible with 1 or 2 miniplates were more or less different from that of the intact mandible. The maximum stress occurred at the biting point. Meanwhile, the subcondylar region was a stress-bearing area. During left unilateral molar clenching, bite forces obviously reduced after fracture. Bite force and the stress distribution pattern in the mandible reduced with 2 miniplates were closer to that in the intact mandible.

Conclusions: It is suggested that the effect of the miniplates in stabilizing the continuity-broken mandible influence the restorations of the stress distribution pattern and bite force. Two miniplates have a biomechanical advantage over 1 miniplate on these restorations.

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Materials and Methods

MANDIBLE MODEL AND MECHANICAL PROPERTIES

The mandible of a 25-year-old man who showed no craniofacial abnormalities was scanned by dual-slice spiral CT (Siemens Somatom DR2; Siemens GmbH, München, Germany) in the axial direction at 0.75-mm intervals. After digitization with MIMICS 11 (Materialize, Belgium), the data were exported to the ANSYS 7.0 program, which created the model from bottom to top. Meshing was performed using Solid 92 finite element. This type of element was used for the 3D modeling of solid structures. The finial model consisted of more than 235,000 elements with more than 375,000 nodes, achieving a highly predictive accuracy for the model. As in a previous study, we assumed mandibular bone to be linearly elastic and isotropic with elastic constants as follows: Young's modulus \( E = 13,700 \text{ MPa} \) and Poisson's ratio \( \nu = 0.3 \) for the cortical bone and \( E = 7,930 \text{ MPa} \) and \( \nu = 0.3 \) for the cancellous bone. The teeth were assumed to be part of the mandible with the same mechanical properties of cortical bone. In this way, the real anisotropic properties of the mandible were simplified, which means that the bone material was assumed to be the same in every plane and would not exhibit any nonlinear stress-strain characteristics or plasticity.

As for the fracture site, we assumed a clear symphyseal fracture in the middle sagittal plane. Contact between the 2 bone segments was assumed to be nonexistent.

FIXATION HARDWARE AND ITS MECHANICAL PROPERTIES

The computer models of the titanium miniplates and monocortical screws were set by the Pro/E program based on physical specimens of the 4-hole, 2.4-mm maxillofacial miniplate (Synthes, Paoli, PA) and a 2.4-mm diameter monocortical screw respectively. The miniplates and screws involved in this study were assumed to be composed of an isotropic elastic material, the elastic coefficients of which are \( E = 1.15 \times 10^5 \text{ MPa} \) and \( \nu = 0.34 \).

Two surgical fixation methods commonly used in symphyseal fracture fixation were developed, namely, fixation with either 1- or 2-plate-screw systems. Each screw was determined to be in perfect contact and firmly fixed with the miniplate (no slip and no clearance) as well as the design of Uni-locking plating system.

CONTACT AND BOUNDARY CONDITION

In this numerical analysis model, it was assumed that the plates were perfectly fixed to the mandibular surface and that the contact between them was frictionless. The tops of the 2 condyles were fixed in space for the boundary condition, and only rotational movement was allowed. The effect of the intermediate articular disc, which acts as a cushion between the condyle and temporal bone, was neglected in this study. The area of concern was well away from the condyle and should not be much affected by ignoring the disc. Teeth restriction is discussed below.

BITING AND MUSCLE FORCES

In the present investigation, 2 basic loading conditions, namely clenching in the intercuspal position (ICP) and left unilateral molar clenching (L-Mol), were investigated. During ICP, the premolars and molars were restrained bilaterally and vertically from movement. During L-Mol, the unilateral premolars and molars were not allowed to move upward. These restraints acted perpendicularly to the occlusal plane (Y axis) at the lower supporting cusps, allowing freedom of displacement in the horizontal plane.

Aiming at simulating realistic muscle forces exerted on the bone when clenching, we used groups of parallel vectors to simulate 9 pairs of masticatory muscles involved in the 2 static biting tasks (superficial and deep masseter; anterior, middle, and posterior, nonunion may increase. Consequently, the determination of best position, orientation, and selection of plate type and materials in the planning stages of fracture treatment are of great importance. However, they have not yet been definitively demonstrated, and existing practical techniques of internal fixation stabilizing fractures of the mandible are mostly based on a surgeon's clinical experience. To guide surgeons to better the effects of RIF, it is essential to reveal the biomechanical behavior of the mandible under different masticatory conditions and to optimize the fixation pattern biomechanically according to the stresses in the mandible and the miniplates resulting from the contraction of the masticatory muscles. Previous research has described the biomechanical distribution of the mandible that fractured at the angle or condylar process after reduction with miniplates of osteosynthesis by using FE analysis. However, the symphyseal fractures have not yet been explored. The present study has 2 main objectives. First, we propose and analyze a 3-dimensional (3D) FE model simulating the behavior of fractured mandibles after reduction with miniplates of osteosynthesis. Second, we use this model to study the response to 2 different masticatory conditions of the mandible that is treated with one or 2 miniplates in the symphysis region, and compare our results to that obtained from an intact mandible. During the fracture-healing period, it is important to restore the bite force. Therefore, the maximum stress on the teeth is also observed to describe the force.
rior temporalis; medial pterygoid; superior and inferior lateral temporalis; and anterior digastric), which were assumed to be directly attached to the bone. The origin and direction of each muscle force was defined from anatomical measurements\textsuperscript{10}. The single vectors of the muscular attachment were as described in the literature\textsuperscript{11}. The magnitude of each muscle force was assigned according to its physiological cross-section and the scaling factor\textsuperscript{12,13}. If the nodes included parts of 2 muscles, their respective force components were vectorially combined\textsuperscript{9}.

With a well-defined geometry and mesh, material properties, and appropriate bite and muscle forces loading, the ANSYS 7.0 finite element solver software was used to compute stress in the models.

**Results**

In this study, we built a 3D FE model of an intact mandible and 2 models of symphyseal fractured mandibles reduced with one and 2 miniplates, respectively. The first model was used for a complete mechanical characterization of physical events. It also provided comparative data for the other 2 models. The evaluation of the FE analysis results was performed with respect to bite forces and stressed areas in the 3 mandibles. The Von Mises stress scalar, running from minimum stress value (blue) to the maximum value (red), represented the general effective stress of the mandible. All stress values were given in MPa.

**MANDIBULAR STRESS DISTRIBUTION IN INTERCUSPAL POSITION**

**Case 1: Intact Mandible**

First the mechanical behavior of an intact mandible was analyzed. During ICP, the stress was symmetrically concentrated on the bilateral mandibular corpora, subcondylar region and anterior aspects of the coronoid processes. We obtained a maximum stress value of 27.778 MPa in the Von Mises stress norm at anterior aspects of the coronoid processes and the mandibular alveolar that received the bite force. While in the chin region, the value was relatively small. The stress distribution of the intact mandible during ICP is shown in Figure 1A.

**Case 2: Symphyseal Fractured Mandible After Reduction**

Stress distribution of the symphyseal fractured mandible after reduction with 1 miniplate or 2 miniplates was depicted in Figures 1B, C, respectively. Except for concentrating on the plates, the stress distribution patterns in the symphyseal fractured mandible after reduction with 1 or 2 miniplates were similar to that obtained in intact mandible during ICP. However, the values


Mandibular stress distribution during left unilateral molar clenching

Case 1: Intact Mandible
The stress concentrated on the bilateral mandibular corpora, chin, and subcondylar region, whereas the stress value in the ramus was small. Stress distribution at the biting side differed from the contralateral side: the subcondylar stress value was higher on the right (nonbiting) side than on the left mandibular side. However the stress value in the corpus was higher on the biting side than on the right (nonbiting) side. The alveolar process of the biting side obtained a maximum stress value of 66.667 MPa in the Von Mises stress norm. Stress values in the right mandibular corpus and the symphysis were 22.222 MPa. The stress distribution in intact mandible was shown in Figure 2A.

Case 2: Symphyseal Fractured Mandible After Reduction
The stressed area in the symphyseal fractured mandible after reduction with one miniplate concentrated on the bilateral mandibular corpora, subcondylar region, whereas the stress value in the chin area was small. As in the intact mandible, the maximum stress value in the Von Mises stress norm occurred at the alveolar process of the biting side, whereas the mean value was smaller than that of the intact mandible. The stressed area in the symphyseal fractured mandible after reduction with 2 miniplates was similar to that in the intact mandible. The left mandibular angle was also a stressed area. The subcondylar stress value was higher on the left side than on the right (nonbiting) mandibular side. The alveolar process of the biting side obtained a maximum stress value in the Von Mises stress norm of 22.778 MPa. The mean value of stress in this mandible was smaller than that in the intact mandible. Stress distribution in the symphyseal fractured mandible after reduction with one miniplate or two miniplates were depicted in Figures 2B, C, respectively.

Bite force of different teeth under various masticatory conditions
It is important to restore the bite forces during the fracture-healing period. The maximum stress on the teeth was also observed to describe the force (given in MPa). The bite forces under various masticatory conditions when the mandible was unbroken or frac-
tured are shown in Figures 3A, B, respectively. We observed a decrease in the bite force during L-Mol in reduced mandibles and a slight increase in the one-miniplate model during ICP.

Discussion

SIMILARITY OF THE MODEL

The most difficult and significant task of the research was the reconstruction of the FE model. Because analytical results of FE analysis are highly dependent on the model developed, the model should be as equivalent to the real object as possible in various aspects. However, various oversimplifications have often been made in studies, making it difficult to match the model with the actual situation and thus the reliability of the results is reduced. In the present study, 3D FE models with more predictive accuracy were developed to evaluate and to analyze mandibular stress distribution after being reduced with miniplates under masticatory conditions.

GEOMETRIC SIMILARITY

In the FE model, an advanced slice spiral CT was used to collect anatomical data from a human mandible. The CT images were obtained from thin collimation (0.5-mm thickness) at small slice intervals (0.75 mm increments), ensuring that all vital topological information was captured precisely. Meshing was performed using Solid 92 finite elements, which is a 3D tetrahedron unit with 10 nodes. Solid 92 finite elements is characterized by quadratic displacement and is especially fit for mesh generation of an abnormal geometric corpus. Each node has 3 degrees of free-
dom, symbolizing displacement in the direction of X, Y, and Z, respectively. The final model consisted of more than 235,000 elements with more than 375,000 nodes, achieving a highly predictive accuracy for the model.

MECHANICAL SIMILARITY

Although bone is an anisotropic material, other researchers mentioned previously showed that isotropic models of the mandible were capable of discerning meaningful stress differences when replicating functional loading. The properties of bone used in our study were compatible with those used by Korioth et al. 9 As in most reported studies, we assumed that the materials were homogenous and isotropic and were a linear elastic behavior characterized by their 2 material constants (Young’s modulus and Poisson’s ratio). For the miniplates and screws, the behavior was also considered homogeneous and isotropic, and this corresponds to the reality.

SIMILARITY OF BOUNDARY CONDITION

The boundary conditions in the FE models represent the loads imposed on the structures under study and their fixed counterparts, and restraints. Loads placed on craniofacial FE models were often oversimplified, intending to simulate so-called “physiological” biting tasks. The oversimplifications lie mainly in their inability to apply the complete range of 3D forces because of the multiplicity of lines of action of the masticatory muscles. In this study, masticatory muscles were not restricted but were loaded along the direction of the muscles that simulated the functional condition of the mandible.

SIMILARITY OF LOADING

Some previous studies14-16 have used point loading to some teeth to simulate the muscle forces. Of course, this could not reflect the biological response of the mandible to the forces. In our study, to simulate the real muscle forces exerted on the bone when clenching, we used groups of parallel vectors to simulate 9 pairs of masticatory muscles involved in the 2 static biting tasks. The values of the force varied under the masticatory conditions.

Predictably, this model was still far from being realistic. Our simulations, like most finite element simulations, were based on an idealized model to which idealized properties (Young’s modulus and Poisson’s ratios) were assigned. As described in Materials and Methods, weaknesses in the model included the lack of information on teeth, the lack of detailed knowledge regarding the material properties of cancellous bone, the uncertainty of how to distribute the muscle loading realistically and the difficulty of knowing how to model the boundary conditions of the condyles. However, as we aimed only at investigating stress distribution and variation rather than predicting the biological reaction, this model was completely qualified for the work. In the future, great importance should be attached to overcoming the shortcomings of the model.

STRESS DISTRIBUTION

As is well known, early and safe mobilization is important for fractured patients after reduction: first, it ensures the provision of all the nutrition the patient needs; and second, it avoids bone loss resulting from lack of physiologic stimulation. However, is it possible that stress distribution of a reduced mandible with miniplates differs from that in the intact mandible during mastication? Will differences between fixation methods cause different influences on stress distribution? Concentrating on these questions, we simulated 2 basic loading conditions, namely clenching in the intercuspal position (ICP) and left unilateral molar clenching (L-Mol), to investigate stress distribution of the mandible reduced with miniplates during mastication and then contrasted the results with those of the intact mandible. Muscle force during the same masticatory condition was assumed constant. As we can notice in Figures 1 and 2, mandibular stress distribution is affected by the way in which the mandible is burdened.

Case 1: Mandibular Stress Distribution During the Intercuspal Position

We notice from Figures 1B, C that the distinction of stress distribution in the 2 models is not obvious. In other words, during ICP, stress distribution in the 2 mandible models both concentrated on the bilateral mandibular corpora, the subcondylar region and the anterior aspects of the coronoid processes symmetrically. This distribution pattern is also similar to that in the intact mandible during ICP. Whereas, among the 3 models, the maximum stress obtained in the intact mandible is the biggest, and the value in the 1-miniplate model is smaller than the values in the other 2 models. These demonstrate that alterations in the stress distribution pattern in the mandible before fracture and after reduction is not obvious; the 2 fixation methods have a similar effect on restoring the stress distribution after fracturing in the mandible; the results obtained from the 2-miniplates model tend to be closer to the intact model than the 1-miniplate model. In general, the observed principal stress was highest on the periosteal cortical surface and alveolar bone; furthermore, the condyle is observed to be a stress-bearing structure, which is in line with previous studies. 9,17
Case 2: Mandibular Stress Distribution During the Left Unilateral Molar Clenching

One of the distinctive findings of our study was that during L-Mol, in all the models, the stress not only concentrated on the biting side but also on the contralateral side (nonbiting), and the maximum stress value occurred at the bite point. As we can see in Figures 2B, C, the area of stress distribution in the 1-miniplate model or 2-miniplates model was smaller or larger, respectively, than that in the intact mandible. The values in the chin region in both of the models were smaller than that in the corpus, and this was more obvious in the 1-miniplate model. The maximum stress value obtained in the intact mandible was the biggest, and the value in the 1-miniplate model was smaller than the values in the other 2 models. In general, the stress distribution pattern in the 2-miniplates model was closer to that in the intact mandible. The authors are not aware of any in vivo studies to compare. To interpret the results, we should pay attention to the loss of mandibular continuity, potential mobilization at the fracture site and the deformation of the mandible when loaded. If a material such as bone is loaded, it undergoes a deformation. Stress is used to quantify the amount of tension occurring in the bone tissue due to the deformation. During clenching tasks, the mandible tends to move upward because of the traction of masticatory muscles, while the teeth are restrained upward on the biting side due to solid food and thus deformation occurs. The comparatively small stress value in the contralateral corpus is probably because of the absence of contacts on this side that cause small deformation. The small stress value in the chin region, corresponding to the deformation, is probably caused by the potential mobilization on the fracture site. To sum up, a loss of mandible continuity causes the alteration of deformation at a certain point under the same loading force; 2 miniplates are better than 1 miniplate with respect to restoring the mandibular continuity and counteracting mobility of the bony segments. Our result is partly in line with Lovald et al.15 In their research, the peak Von Mises stress in cortical bone occurs ipsilaterally to the bite force.

In addition, according to the description above, it is clear that the condyle is the ultimate destination of the major stress trajectories within the mandible. There can be little doubt that the condyle is loaded during bilateral and unilateral functions.

BITE FORCES

Postoperative mastication is of great importance to fractured patients. Bite force is an essential factor in mastication activity. Previous studies18,19 have reported a reduction in bite force occurring for several weeks postinjury. They have assumed that the protective neuromuscular mechanisms occurring throughout the body and the traumatic and surgical damage to the masseter and temporalis muscles could account for that phenomenon. In our study, the muscle forces were constant in the same masticatory condition. We can observe a reduction of bite force during L-Mol in reduced mandible (Figs 3A,B). However that reduction is not obvious during ICP; instead, the bite force shows a slight increase in the 1-miniplate model during ICP (Figs 3A,B). In both of the 2 biting tasks, the bite forces in the 2-miniplates model are closer than that in the 1-miniplate model to the bite force in the intact mandible. This is probably because of the relatively small amount of mobility in the bony segments in the 2-miniplates model. During L-Mol, the nonbiting side has a smaller upward movement because of the mobility of the fracture site; thus the stress on the teeth that means bite force in our study is smaller than that in the intact mandible.

The significance of these findings is that a loss of mandibular continuity may also lead to a decrease in bite force. Guaranteeing an effective method of fracture stabilization and improving fracture stability at the fracture site by producing a secure joint of the fracture segments, 2 miniplates have an advantage over 1 miniplate for restoring bite force.

References