A biomechanical analysis of titanium miniplates used for treatment of mandibular symphyseal fractures with the finite element method

Baohui Ji, Chun Wang, Lei Liu, PhD, MD, Jie Long, PhD, MD, Weidong Tian, PhD, MD, Hang Wang, PhD, MD, Chengdu, PR China

SICHUAN UNIVERSITY

Objective. This study aimed to evaluate the stress distribution and stress shielding effect of titanium miniplates used for the treatment of symphyseal fractures using finite element (FE) analysis.

Study design. Two 3-D FE models of symphyseal fractured mandibles reduced by technique 1, reduction with a single miniplate, and technique 2, reduction with 2 miniplates, respectively, were developed. Three basic loading conditions were simulated.

Results. The ratios of stress shielding of miniplates were different. Ratios of the lower miniplates in technique 2 were much higher than the upper miniplates and the miniplates in technique 1 during all conditions, and that value of the lower miniplate gained a maximum value of 83.34% during left unilateral molar clenching. The stress areas were concentrated on the central section of the miniplates. However, the stress distribution varied with masticatory conditions.

Conclusion. The study demonstrated that miniplate stress distribution and stress shielding effect ratio were affected not only by the way in which the mandible was loaded but also by the number of the miniplates fixing the fracture. (Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2010;109:e21-e27)

The symphysis is one of the most frequently fractured regions after traumatic events involving the mandible, with a frequency of 9% to 57%. Rigid internal fixation is now routinely used for surgical management of mandible fractures. The stability of the mandible during functional activities takes the premier place in this technique. Indeed, movement at a fracture line is a known predisposing factor for both infection and non-union. Thereby, the ideal plate-screw system must be strong and rigid enough to withstand the functional loads and enable undisturbed fracture healing. In addition, the concept of “stress shielding” should also be taken into account. A too rigid plate will lead to bone loss. Given these facts, optimized internal fixation should attain a balance between the stability of the fragments and the stress shield effect of the miniplates.

In past decades, finite element (FE) analysis, which is based on material properties to determine the distribution of stress and strain when the structures are subjected to force, was applied to stress-strain analysis for complex structures. Previous research has already described the biomechanical distribution of a mandible that fractured at the angle or condylar process after reduction with miniplates using FE analysis. However, the symphyseal fracture has not yet been explored. For these reasons, in the present study, we proposed and analyzed two 3-dimensional (3-D) FE models simulating the behavior of symphyseal fractured mandibles after reduction with titanium miniplates. We then used these models to study the response to 3 different masticatory conditions of the mandible that were treated with 1 or 2 miniplates in the symphyseal region.

MATERIALS AND METHODS
The mandible model and its mechanical properties

A human mandible of a 25-year-old man, who showed no craniofacial abnormalities, was scanned by dual-slice spiral computed tomography (CT) (Siemens Somatom DR2, Siemens GmbH, Munchen, Germany) in the axial direction at 0.75-mm intervals. After being digitized with MIMICS (Materialise, Leuven, Belgium), the data were exported to the Ansys 7.0 program, which created a model from bottom to top. Meshing was performed with the use of Solid 92 finite element. Finally, we assumed that the mandible had linearly elastic behavior, and its mechanical properties

This work was supported by the National Natural Science Foundation of China (10702046).

State Key Laboratory of Oral Disease, Sichuan University, Chengdu, PR China.

Department of Oral and Maxillofacial Surgery, West China Hospital of Stomatology, Sichuan University, Chengdu, PR China.

Received for publication May 11, 2009; returned for revision Oct 17, 2009; accepted for publication Nov 8, 2009.

1079-2104/5 - see front matter
© 2010 Published by Mosby, Inc.
doi:10.1016/j.tripleo.2009.11.003

e21
could therefore be described by the Young’s modulus \((E)\) and Poisson’s ratio \((\nu)\). As in previous work,\(^7,14\) we assumed the mandible to be elastic and isotropic with elastic constants \(E = 13,700\) MPa and \(\nu = 0.3\) for the cortical bone and \(E = 7930\) MPa and \(\nu = 0.3\) for the cancellous bone. The teeth were assumed to be part of the mandible with the same mechanical properties. In this way, the real anisotropic properties of the mandible were simplified, which means the bone material was assumed 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 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 thickness maxillofacial miniplate (SYNTHES, West Chester, 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, whose elastic coefficients are \(E = 1.15 \times 10^5\) MPa and \(\nu = 0.34\). Each miniplate was fixed to the mandible by 4 monocortical screws.

Two different surgical fixation techniques, which were commonly used in symphyseal fracture fixation, were then developed (Fig. 1). In technique 1, a single miniplate was fixed horizontally in the middle of the symphysis. In technique 2, 2 miniplates parallel to each other were used. One miniplate was fixed onto the lower part and the second one was fixed immediately below the dental roots and above the lower dental nerve, in accordance with the work of Champy et al.\(^15\)

Each screw was determined to be in perfect contact and firmly fixed with the cortical and trabecular bone surrounding it and the miniplate (no slip and no clearance) as the design of Uni-locking plating system. Furthermore, the miniplates were assumed not to receive or transmit any force directly from the bone segments, rather, the chain of force transfer was defined as progressing from bone to screw, from screw to plate, and finally returning via the screws back to the bone.

### Contact and boundary condition

To prevent the rigid corpus translation and/or rotation during biting on an object, the top of the 2 condyles were fixed in space for the boundary condition and only rotational movement was allowed. The effect of the intermediate articular disk, 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 disk. Restriction of the teeth will be detailed in the following section.

### Biting and muscle forces

In the present investigation, 3 static biting tasks, namely clenching in the intercuspal position (ICP), incisal clenching (INC), and left unilateral molar...
clenching (L-MOL) were simulated. In ICP, the premolars and molars were restrained bilaterally and vertically from movement (excluding the third molar, which was partially erupted). During INC and L-MOL, the 4 incisors and the first molar, respectively, were not allowed to translate upward. These restraints acted perpendicularly to the occlusal plane (y-direction) 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 pairs of parallel vectors to simulate 9 pairs of masticatory muscles involved in the 3 static biting tasks (superficial and deep masseter; anterior, middle, and posterior temporalis; medial pterygoid; superior and inferior lateral temporalis; and anterior digastric). The origin and direction of each muscle force was defined from anatomical measurements. Their directions were derived algebraically as unit vectors (i.e., direction cosines). The single vectors of the muscular attachment were available in the literature. Their directions were derived algebraically as unit vectors (i.e., direction cosines). The single vectors of the muscular attachment were available in the literature.16 The magnitude of each muscle force was assigned according to its physiological cross section and the scaling factor.18,19 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. After fixation, miniplate and bone directly under it form one mechanical system, and the stress that the miniplate bears accounts for a certain proportion to the bone stress when there is no miniplate. This proportion was defined as the stress shielding ratio in our study. A local stress shielding ratio of the miniplate was also calculated according to the formula

\[ \eta = \left( 1 - \frac{\sigma}{\sigma_0} \right) \times 100\% , \]

where \( \sigma \) is the stress of the bone directly under the miniplate after fixation, and \( \sigma_0 \) is the stress of the bone of the same site before fixation.

**RESULTS**

The Von Mises stress’s scalar running from minimum stress value (blue) to the maximum value (red) represented the general effective stress of the miniplates. All stress values were given in MPa.

The ratios of stress shielding in both of the models are shown in Fig. 2. When the mandible was fixed with 1 miniplate, the ratios during ICP and INC were both 50%, but the ratio was smaller during L-MOL. When the mandible was fixed with 2 miniplates, the values changed. As shown in Fig. 2, the ratios of the 2 miniplates in technique 2 not only differed from each other, but also differed from that of the single miniplate in technique 1. In general, the value of the lower miniplate was much higher than that of the upper miniplate and the single miniplate in technique 1 during each condition, and it gained a maximum value of 83.34% during L-MOL. For the upper miniplate, the value during INC was higher than its value during the other 2 conditions, and the value during ICP was the lowest. In contrast with the upper miniplate, the lower miniplate gained its minimum value during INC.

---

Fig. 2. Ratios of stress shielding of miniplates during different masticatory conditions.
The maximum stress values of different miniplates are shown in Fig. 3. The stress distributions of different miniplates are shown in Fig. 4. In general, the stress areas were concentrated in the central part of the miniplates. The magnitude of the stress on the upper miniplates in technique 2 was smaller than that on the lower miniplates during all conditions. The superior and inferior boundaries covering the fracture line gained the maximum stress in every miniplate; however, the stress distribution varied with masticatory conditions. During ICP, the stress of the 2 holes close to the fracture line concentrated on the part farthest away from the fracture line, whereas for the other 2 holes, the stress concentrated on the part closest to the fracture line. During INC, the stress concentrated on the 2 holes just alongside the fracture line. We also would like to point out that the maximum stress values of the screws were uniformly higher than those of the miniplates. Moreover, the 2 screws farthest away from the fracture line gained the maximum value.

DISCUSSION

Previous authors have reported a reduction in bite force occurring for several weeks post injury. However, a uniform agreement of the magnitude of the bite forces has not been arrived at. In our study, the muscle forces were consistent with the values of an intact mandible. Of course, these models were 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 the Methods section, weaknesses in the model included the lack of information on teeth, the lack of detailed knowledge regarding the material properties of the cancellous bone, the uncertainty of how to realistically distribute the muscle loading, and the difficulty of knowing how to model the boundary conditions of the condyles. However, as we only aimed at investigating stress distribution and variation rather than predicting the biological reaction, these models were completely qualified for the work. In the future, great importance should be attached to overcoming the shortcomings of the model.

The effect of stress shielding is well known in long bones. The scientific evidence to date strongly suggests that bone loss in plated long bone is caused by stress shielding, and not interference with cortical perfusion secondary to bone–plate contact. Kennady et al. documented decreased mandibular bone volume as well as smaller interlabile width on the plate side, suggesting a stress shielding effect as a result of the rigid internal fixation plate. Dechow et al. stated that bone strain inferior to the plates was reduced by 34% to 53% after attachment of the plates. However, long-term placement of bone plates, and the resulting stress shielding were not found to result in structural changes in the mandibular corpus. Because of their different methods and goals, the results are different. Nevertheless, we should point out that neither of them revealed the stress shielding effects when a load shearing plate was used to plate the fracture fragments. To our knowledge, no
study has been published providing definite data revealing the stress shielding effects when titanium miniplates are used to immobilize mandibular symphyseal fractures.

The results of our study indicate that mandibles fixed with titanium plates also experience stress shielding as long bones. Moreover, the value varies with fixation sites even though the mandible is under the same loads. It also varies with masticatory conditions even though the miniplate is fixed in the same place (Fig. 2). In our previous study,\textsuperscript{26} we found that under a certain masticatory condition the mandible gained different values at different sites, and the same area gained different val-

Fig. 4. A, The Von Mises stress of the miniplate in technique 1 during ICP. B, The Von Mises stress of the miniplate in technique 1 during INC. C, The Von Mises stress of the miniplate in technique 1 during L-MOL. D, The Von Mises stress of the miniplates in technique 2 during ICP. E, The Von Mises stress of the miniplates in technique 2 during INC. F, The Von Mises stress of the miniplates in technique 2 during L-MOL.
ues when the load was changed. Therefore, based on these studies, we can draw the conclusion that the ratio of stress shielding correlates with the way in which the mandible is burdened and the number of miniplates fixing the fracture. The important question, however, is whether the amount of stress shielding observed is biologically significant. It will therefore be necessary in future studies to determine whether the amount of stress shielding found in this study is a clinically significant problem after the fixation of symphyseal fractures.

It is well known that a mandible is normally subjected to bending forces at its upper boundary part and to compression forces at its lower boundary, and the symphyseal region is the very area bearing torsion forces as well as tension forces. In a mandible symphyseal region is the very area bearing torsion to compression forces at its lower boundary, and the problem after the fixation of symphyseal fractures. The important question, however, is whether the amount of stress shielding observed is biologically significant. It will therefore be necessary in future studies to determine whether the amount of stress shielding found in this study is a clinically significant problem after the fixation of symphyseal fractures.

In summary, the present study evaluated the biomechanical behavior of 2 different techniques used in plating the fractured mandibular symphysis. Three-dimensional FE methods were used to calculate the stress value in Von Mises form and the stress shielding effect ratio of the miniplates. Our results demonstrated that stress distribution and miniplate stress shielding effect ratio are affected not only by the way in which the mandible is burdened, but also by the number of the miniplates fixing the fracture.

REFERENCES


Reprint requests:
Hang Wang, PhD, MD
State Key Laboratory of Oral Disease
Sichuan University
Chengdu 610041, PR China
dentistwh@gmail.com