Finite Element Analysis of Two- and Three-Dimensional Fixation in Treating Mandibular Symphyseal Fracture Combined With Bilateral Condylar Intracapsular Fractures

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Abstract: The aim of this study was to compare through finite element analysis two- and three-dimensional (2D and 3D) fixation in the treatment of mandibular symphyseal fracture combined with bilateral condylar intracapsular fractures. The authors created 2 fixation models for the above fracture, and analyzed the stress and displacement in the mandible and fixation materials under 3 loading conditions. The von Mises stress of the mandible and plates peaked during lateral occlusion, and was lowest during central occlusion. In all conditions, stresses in the fixation materials did not exceed the yield stress of titanium. The inferior border of the symphyseal fracture segments showed opposing displacements, and the mandible tended to widen in the 2D fixation model. However, the fracture displacement did not exceed 150 μm for either fixation method. The results suggested that after well reduction and fixation of condylar intracapsular fractures, either 2D or 3D fixation for symphyseal fracture can provide adequately strong fixation. Compared with 2D fixation, 3D fixation has more advantages in controlling the mandibular width and preventing the fixation materials from enduring excessive stress.

Key Words: Condylar intracapsular fracture, finite element analysis, rigid internal fixation, symphyseal fracture, three-dimensional fixation

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The mandible is the most frequently fractured bone after traumatic events involving the maxillofacial region, fracturing in 36% to 70% of cases.[1] Among multiple mandibular fracture types, symphyseal–condylar fractures are the most common.[2] Although open reduction and internal fixation for most mandibular fractures is widely accepted as best practice, the selection of a suitable fixation method is crucial to healing and restoration of masticatory function. Several studies have investigated the efficacy of various fixation methods in the treatment of mandibular isolated fractures, such as symphyseal fracture.[3,4] However, the specific behavior of each mandibular region during force application must be considered. Complications are therefore possible in assessing multiple fractures, whereby the treatment of each fracture could affect the whole mandibular force distribution,[5] making results for a single fracture possibly not immediately applicable to multiple fractures.

Symphyseal–condylar fractures, especially bicondylar fractures, are particularly difficult to treat because of the increase in splaying and the loss of the transversal and sagittal dimensions. According to Association for the Study of Internal Fixation, the treatment of mandibular symphyseal fracture combined with bilateral condylar intracapsular fractures must reduce and stabilize the symphyseal fracture to ensure mandibular width control.[6] Therefore, the symphyseal fracture should be fixed strongly with such as a reconstruction plate or lag screws. Two parallel miniplates fixed on the buccal surface of the mandible (two-dimensional, or 2D, fixation) is also efficient and widely used. Progress in fixation techniques has led to three-dimensional (3D) miniplate fixation being gradually applied clinically. It has been reported to minimize bending and torsion movements, which are the most important biomechanical movements occurring in the anterior region of the mandible.[7]

The testing of new fixation methods should undertake biomechanical analysis. Finite element (FE) analysis can obtain the stress, strain, and displacement of bones and plates. It is applied here to compare 2D and 3D fixations for treating mandibular symphyseal fracture combined with bilateral condylar intracapsular fractures.

MATERIALS AND METHODS

Construction of the Mandibular Models

A human mandible of a 25-year-old male volunteer—who showed no craniofacial abnormalities, no temporomandibular joint (TMJ) disorders, and no third molars—was scanned by maxillofacial computed tomography (CT) and TMJ magnetic resonance imaging. The CT data were exported to the ANSYS program (ANSYS Inc, Southpointe, PA) to create a model of the mandible and partial temporal bone with the glenoid fossa. The magnetic

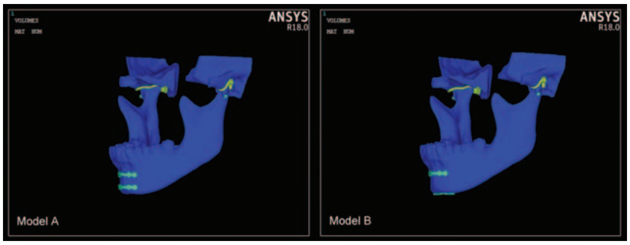

FIGURE 1. (A) Two- and (B) three-dimensional fixation models.

resonance imaging data were exported to the Geomagic program (Geomagic Inc, Research Triangle Park, NC) to create a model of the disc. The models of the mandible, temporal bone, and disc were integrated into a single model according to their actual anatomical locations. After meshing using solid 92 element, 3 linear fractures were simulated by 0.1 mm wide gaps. One fracture was in the middle of the mandible; the others were symmetrical in the lateral 1/3 of the condyles (Neff B fractures). Neff B condylar fractures were simulated as they usually need surgical reduction.[8] Plates and screws were reconstructed using digital models provided by the manufacturer (Cibei, Ningbo, China). The plate models were bent on the computer to fit the contour of the mandible.

Construction of Osteosynthesis Models

Two different fixation models for the symphyseal fracture were developed. Model A was a 2D fixation model incorporating 2 parallel miniplates on the buccal surface of the mandible: one on the subapical region, and the other on the inferior border of the mandible. Model B, with 3D fixation, had the upper plate maintained in the same position, and the lower plate was located under the lower edge of the mandible. Both models had the condylar intracapsular fracture fixed uniformly with a single 18 mm screw. The plates were assumed not to transmit or receive any force directly to or from the segments. Finally, the plates and screws were integrated with the bone in both models using Boolean operation (Fig. 1).

Material Properties

The models were considered isotropic and linear elastic. Using the material assigning function in Mimics (V 12.0, Materialize, Leuven, Belgium), the HU values from the CT images of the mandible were divided into 10 groups (Supplementary Digital Content, Table 1, http://links.lww.com/SCS/C548). Bone density (ρ) and elastic modulus (E) were calculated as follows[9]:

$$\rho = 114 + 0.916\,\mathrm{HU}, \tag{1}$$

$$E = 0.51\rho^{1.37}. \tag{2}$$

By considering the heterogeneity of bone in this way, the models had improved mechanical properties. The Poisson ratio (υ) of the bone was 0.3. The modeled plates and screws had $\upsilon = 0.34$ and $E = 1.15 \times 10^6$ MPa.

Contact and Constrains

Three static biting tasks were simulated: intercuspal position (ICP), incisal clenching (INC), and right unilateral molar clenching (R-MOL). In ICP, the bilateral molars were vertically restrained. The vertical freedom was restricted for four incisors in INC and for the right molars in R-MOL. In all occlusion tasks, the superior surface of the temporal bone was fixed in all directions, allowing movement and rotation of the condyles in the fossa. Contact was set for the TMJ fossa, the articular disc, and the condyle. Friction at the articular surface was ignored.

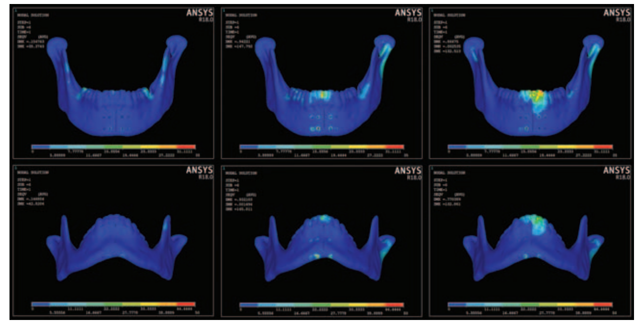

FIGURE 2. Stress distribution in mandibular models during intercuspal position (left), right unilateral molar clenching (middle), and incisal clenching (right).

Loads

Four pairs of parallel vectors were used to simulate the masticatory muscles (masseter, medial pterygoid, anterior, and posterior temporalis). The origin and direction of each muscle was determined from its anatomical position. The magnitude of each muscle force was assigned from the literature, according to the occlusion task[10] (Supplementary Digital Content, Table 2, http://links.lww.com/SCS/C548).

RESULTS

The von Mises stresses of the mandibles concentrated on the occlusive surfaces and bones around the screws under all conditions (Fig. 2). As shown in Supplementary Digital Content, Table 3, http://links.lww.com/SCS/C548, both models had greatest stress during R-MOL, and lowest during ICP. There was no significant difference in the stress distribution between the 2 fixation methods.

Von Mises stresses of the plates are shown in Fig. 3. The lower miniplate had significantly higher stress than the upper miniplate, especially when the symphyseal fracture was 3D fixed. In general, the screws had uniformly higher stresses than the plates (Supplementary Digital Content, Table 4, http://links.lww.com/SCS/C548), although the stresses remained within safe limits. Greater stresses developed on plates and screws during R-MOL than during ICP or INC, similar to the stress distributions in the mandible. For model A, the stress mainly concentrated on the buccal surface of the plates (arrow, Fig. 3). For model B, the lower plate displayed stress concentration on the superior and inferior boundaries, where the

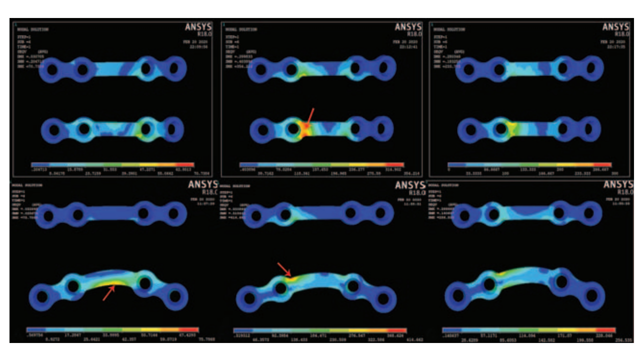

FIGURE 3. Stress distribution in plates during intercuspal position (left), right unilateral molar clenching (middle), and incisal clenching (right) in models A (top) and B (bottom). The arrows indicate stress concentrations.

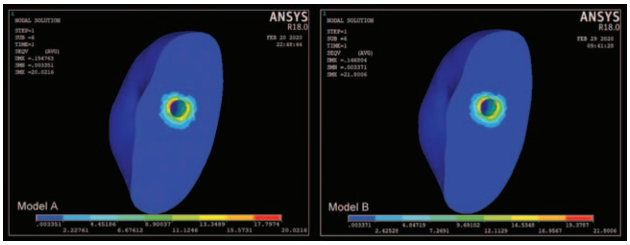

FIGURE 4. Von Mises analysis of stress distribution of the condylar intracapsular fracture surface. No significant difference was observed between the 2 models.

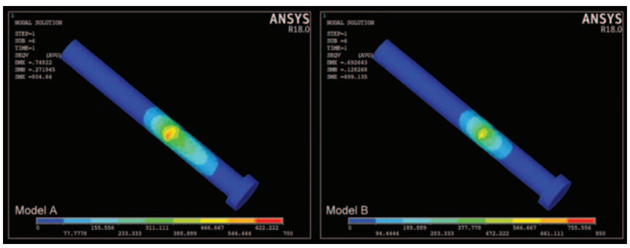

FIGURE 5. Stress distribution of the condylar long screw. The 2D fixation model (left) showed an area of high stress (red) and a wider range of stress distribution.

plate was bent laterally (arrow, Fig. 3). Comparing the 2 fixation methods shows that 3D fixation led to lower stresses on the screws.

The von Mises stresses of bilateral condyles were symmetrically distributed under INC and ICP. Therefore, the right condyles were selected for stress analysis. No significant difference was observed in the stresses of medial condyles between the 2 fixation methods (Fig. 4). Supplementary Digital Content, Table 5, http://links.lww.com/SCS/C548 lists the maximum stresses of condylar long screws in all conditions. The stresses during R-MOL were greater at the contralateral condyle and screw than at the ipsilateral condyle and screw. Comparing the 2 fixation methods, both the magnitude and distribution of the stresses on the condylar screw were larger for 2D fixation (Fig. 5).

The transverse displacement results from the 2 models for ICP are shown in Fig. 6. In model A, the inferior border of the symphyseal fracture segments near the lingual fracture line showed opposite displacements, and the mandible tended to widen (arrow, Fig. 6). In model B, however, no apparent displacement was observed at the symphyseal fracture line. Supplementary Digital Content, Table 6, http://links.lww.com/SCS/C548 lists the maximum displacements of the mandibles: model A had consistently higher values under all conditions. The relative displacements of the symphyseal and condylar fracture segments are shown in Fig. 7. Neither model incurred a displacement greater than the safe limit of 150 μm.

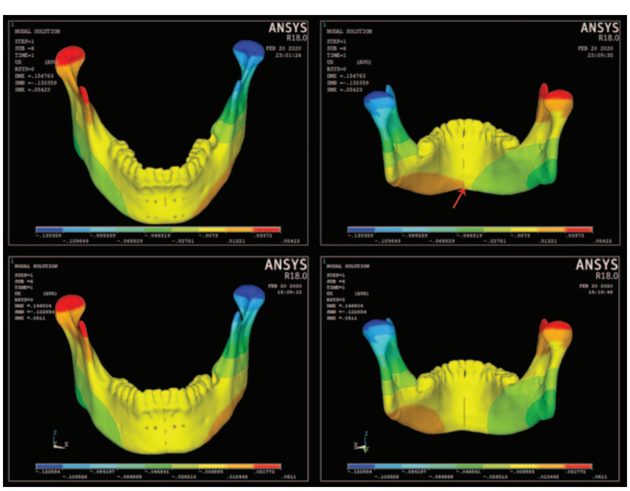

FIGURE 6. Nephograms showing transverse displacement in models A (top) and B (bottom). The two-dimensional fixation model showed displacement in the symphyseal fracture (indicated by an arrow) and the mandible tended to widen.

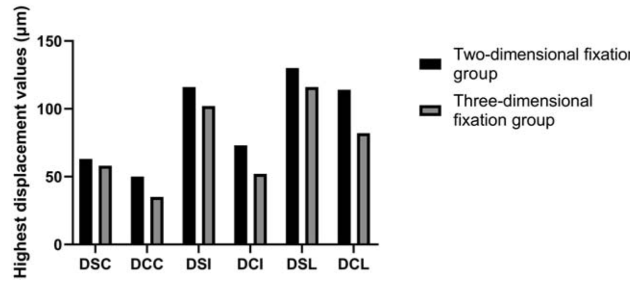

FIGURE 7. Maximum displacement during various loading conditions. In the abbreviations the initial D denotes displacement; the following S or C, respectively denotes the symphyseal and condylar intracapsular fractures; and the final C, I, or L denotes central, incisor, and lateral occlusion, respectively.

DISCUSSION

Fracture is caused by the external force on the bone exceeding its limit strength, inducing mechanical decay. Fracture healing is a process of redistributing and recombining stress.[11] Biomechanical principles state that fixation should not only be able resist tensile, torsional, and shear stresses (which are detrimental to bone healing), but also provide adequate compressive stress.[12] As open reduction and internal fixation is widely performed clinically, determining a predicable protocol for fixation is important. Previous comparisons of various fixation techniques mainly relied on clinical observation of complications and radiography, such as CT measurements of fracture displacement.[13] Finite element analysis can efficiently evaluate biomechanical behavior, and can analyze stress and displacement after fracture fixation.

Previous FE studies commonly used a simplified bite force applied perpendicularly to the occlusal plane.[3,14] Although the magnitude of the load may be similar to that of masticatory forces, its location and direction are different, which may affect the stress distribution. The present study simulated several pairs of muscles, and the forces were applied to the actual muscle attachment areas to obtain the precise mandibular displacement caused by muscle traction. Ellis and Throckmorton[15] reported that the maximal bite forces were approximately 60% of the baseline bite force 6 weeks after operation. Our study applied normal muscle forces, resulting in stresses that may be greater than in practice. This overestimation ensures that the stress intensity of the plates and screws satisfies the actual needs of occlusal function in postoperative patients.

Primary bone healing requires rigid fixation and immobility of fracture segments with a minimal gap of <0.1 mm.[16] The present study simulated interfragmentary gaps of 0.1 mm, consistent with Jesus et al.[14] Wang et al's comparison of values of 1 mm and 0.1 mm[16] found no significant difference in the stress distribution of bony segments, but the plate system withstood more loads in the 1 mm condition. Murakami et al[17] simulated 3 contact conditions of bony segments (direct contact, defect, and callus layer), and studied the effect of minimal interfragmentary gap on reducing stresses on the plates.

In the present study, the mandible and fixation system had the least von Mises stresses during ICP, and the greatest during R-MOL. Murakami[17] and Ji[4] also found the greatest stress during lateral occlusion clenching. The smaller stress during ICP—which is conducive to fracture healing—were expected. Therefore, central occlusion should be recommended for postoperative patients to prevent plates from excessive stress. In addition, during lateral occlusion, the stress of the contralateral condyle was greater than that of the ipsilateral condyle. The FE study of Ji et al[4] also reached the same conclusion. This is because stress conduction during lateral occlusion is like a lever with its fulcrum on the occlusal tooth, and the contralateral condyle is located on the longer arm of force, resulting in greater torque.

Comparing the 2 fixation methods found the same stress pattern, with the main concentration around the holes of the plates near the fracture line, rather than at the bridges of the plates. We therefore assume this site to be prone to fracture, although this requires clinical verification. The 2 fixation methods differed in that the stress was mainly distributed on the buccal surface of the lower plate in model A, whereas it was mainly distributed on the superior and inferior edge of the lower plate in model B. This may have been due to the lower plate in 3D fixation being bent laterally to fit the contour of the mandible, resulting in stress concentrating in the sinuosity place. Therefore, iterative bending, especially lateral bending, should be avoided in practice to prevent areas of excessive stress concentration and destruction of the material structure.

The present study found that the stress in the inferior plate was always higher than that in the superior plate regardless of the fixation method. Ji et al[4] evaluated the mechanical behavior of symphyseal fractures fixed by 1 plate or 2 parallel plates, finding that the maximum stress of the lower plate was much higher than that of the upper plate and the single plate. The stress distribution between the 2 plates was more greatly imbalanced in the 3D fixation than in the 2D fixation, possibly because the inferior plate resisted not only the shear stress, but also the torsional stress produced by fracture segments. These results indicate that the fixation of the inferior plate is more important, especially for 3D fixation. Therefore, if fixation with a large plate (for example, of size 2.0 mm) if necessary, accurate reduction of the fracture, closure of the interfragmentary gap, and proper fitting of the plate with the mandible are critical to prevent fracture of the inferior plate. The stresses of fixation materials in both models did not exceeded the yield stress of titanium (934 MPa)[18] in our study, indicating that both methods achieve adequate fixation strength. However, the stress on the screws was significantly higher in 2D fixation than in 3D fixation, and represented an increased risk of screw fracture or loosening.

Previous work has shown that any alteration of the force distribution at the symphyseal fixation would consequently affect the condylar region.[5] The present study compared 2 methods of the symphyseal fracture fixation, while the condylar intracapsular fracture was fixed uniformly with a long screw. The magnitude and range of stress on the long screw in 2D fixation were larger than those in 3D fixation. This could mean that when the symphyseal fracture is 2D fixed, greater stress is transmitted to the condylar region, resulting in greater stress at the condyle–screw interface. Differing stresses on the condylar region induced by different symphyseal fixation methods is also confirmed in the literature.[17] Oliveira et al[5] proposed that when the symphysis was fixed stably, condylar fixation was less required. However, tension and displacement in the condyle would increase if the symphyseal fixation was less effective. In our opinion, applying 2D fixation to symphyseal fracture increases the requirement for rigid and stable fixation of condylar intracapsular fracture. Fixation using 2 long screws may be suitable to avoid fracture displacement.

Given that movement at a fracture line is a predisposing factor for both infection and nonunion, analyzing fracture displacement can effectively evaluate the fixation stability.[19] In the present study, mandible displacement under the three conditions of 2D fixation was higher than that in 3D fixation. Therefore, 3D fixation had more advantages in maintaining the stability of fracture segments and mandibular width control. The displacement nephogram (Fig. 6) showed that the inferior border of the segments near the lingual fracture line oppositely displaced and that the mandible tended to widen in 2D fixation. However, the relative displacement of the symphyseal and condylar fracture segments remained within the safe limit of 150 μm[20] under all conditions in both models, indicating that both fixation methods provided the basic conditions for normal fracture healing. Therefore, the selection of fixation method for symphyseal fracture combined with bilateral condylar intracapsular fractures should be determined according to the specific conditions. For example, 2D fixation would be applicable in the following circumstances: no maxillary fracture; no loss of teeth, especially posterior teeth; bilateral condylar intracapsular fractures not comminuted and stably fixable; linear symphyseal fracture without defect. This is because after reduction and fixation of condylar intracapsular fractures, the factor of mandibular widening is reduced. There is also a stable occlusal relationship after reduction of the symphyseal fracture. Such cases are equivalent to isolated symphyseal fracture. However, in cases contrary to the above conditions, a more rigid fixation such as 3D fixation should be considered to maintain the width of the mandible.

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