

Evaluation of threshold stress for bone resorption around screws based on in vivo strain measurement of miniplate

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Abstract

The purpose of this study is to investigate the critical threshold stress causing bone resorption evaluated from strain measurement in vivo, comparing the various finite element models. In this study strains of miniplates used for mandibular fractures were measured once a week until the strains reduced. The maximum bite force for each patient was applied in the incisal, right molar and left molar region. The strains increased and reached a peak level at 2-4 weeks, whereas the bite forces increased during the period of measurements. A 3-D osteosynthesis model using finite element method showed that the compressive stresses of the bone surrounding screws ranged within approximately -40 MPa under the condition generating the same amounts of strains measured in the miniplates. Furthermore, various finite element models simulating mandibular reconstruction using the fibular graft were constructed. The models for reconstruction using single strut fibula showed distinct stress concentration in the cortical bone surrounding screws, and the peak stress levels were 2 to 3 times as strong as that of the fracture model. We conclude that critical threshold for bone resorption should be approximately -50 MPa (3600 μ strain).

Keywords: Mandibular Fractures, Threshold Stress, 3-D Osteosynthesis Model, Finite Element Analysis

Introduction

To avoid postoperative mechanical loosening of screws caused by excessive loads, it is important to determine the nature of stress distribution in the bone surrounding the biomaterials^{1,2}. Numerous biomechanical studies on implantation revealed that there is a direct correlation between high-stressed region and bone resorption. In particular, loosening of screws and bone resorption is associated with high peak stresses at the interface in the immediate postoperative stage^{3,4}. However, any estimation of the absolute value of the threshold stress for bone resorption has never been established.

Miniplate osteosynthesis has become a standard treatment of mandibular fracture treatment and reconstruction in oral and maxillofacial surgery. Nevertheless, load bearing of miniplates and bone has been less known accurately. In reconstructive surgery, screw loosening has occurred frequently. Furthermore, even in fracture treatment, it is reported that many screws had already

loosened at the time of removal of the plates, however, fracture healing was only seldom disturbed⁵. This led us to postulate that the critical threshold for bone resorption would not be so much higher than the stress level that is generated in the clinical fracture treatments.

In this study, in order to clarify physiological stress level for the bone surrounding screws, we measured in vivo changes in stress-bearing of miniplates and simulation of stresses loading the bone around screws using the three dimensional (3-D) finite element models during the healing process in mandibular fracture. Subsequently, various finite element models simulating mandibular reconstruction using the fibular graft were prepared, and stress analyses were performed. The purpose was to investigate the critical threshold stress causing bone resorption, comparing the various finite element models.

Materials and Methods

A. Patients

Four patients with mandibular fracture, ages ranging from 17 to 48 years (mean, 30) were the volunteers for this study with cooperative consent. The procedures were carried out after approval from the institutional ethics committee in Nara Medical University. Three patients had sustained

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fractures at the angle region, one at the body (Fig. 1). All cases were typical mandibular fractures, having the dentate mandible.

B. Surgery and strain gauge implantation

All patients underwent intraoral open reduction and fixation with miniplates. In case 4, which was an old fracture, the callus was removed and refractured because both the fragments were deviated and united. After reducing the bone fragments, straight-shaped four-hole noncompression miniplates made of titanium (Champy, Martin Co, Tuttlingen, Germany) were adjusted to the cortical bone without bending their mid-portion. Using a cyanoacrylate monomer strain-gauge adhesive, the single-element strain gauges (Kyowa, Tokyo, Japan) were attached on both inner and outer surfaces of the miniplates at the mid-portion, parallel to their long axis. Miniplates were placed along the ideal line of osteosynthesis⁶: a miniplate was contoured to the superior buccal cortical area of the mandible. The lead wires emerged through the oral mucosa and were covered with a polyethylene tube for protection. After surgery, patients were allowed to masticate normally.

C. Strain measurements

Strain measurements were carried out every week until strain decreased. To measure strains, the leads from the gauges were connected to a personal computer through a digital strain amplifier board (Kyowa), sampling at a rate of 50 Hz. The maximum bite force of each patient was applied to the incisal, the right molar and the left molar region (Fig. 1). The bite point at which bite forces could not be measured normally because of tooth fracture or subluxation was excluded from the measurements. The bite forces were

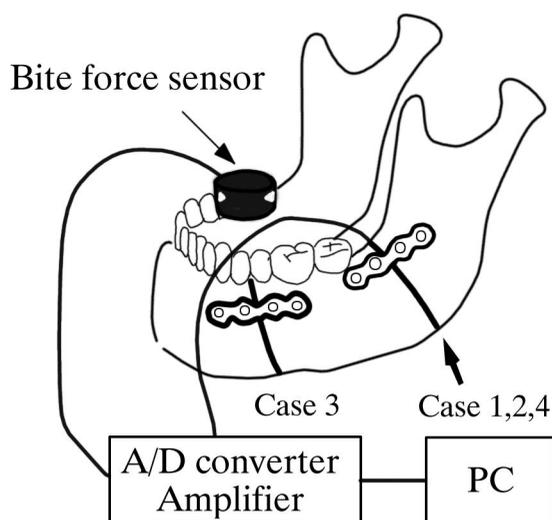


Figure 1. Schematic diagram of measurements and miniplate fixation in mandibular fractures.

measured with a bite force sensor with strain gauges at least eight times for each site. Before each measurement, the strain in the relaxed position of the mandible was initialized as zero strain.

D. Simulation of the bone stress for mandibular fracture

Three-dimensional finite element models for the mandibular fracture fixed with a miniplate and screws were prepared to investigate the nature of stress distributions in the cortical bone surrounding the screws in response to a tensile force of the miniplate (Fig. 2). The mandible has three layers, namely the buccal cortical bone 3 mm thick, cancellous bone and lingual cortical bone 1 mm thick, based on the generated eight node solid element. The material properties of this model were assumed to be homogeneous, isotropic and linearly elastic. The screws were inserted into the bone 5 mm in depth. Nodes of a miniplate and screws were joined to each other. As for the interface condition between bone and plate, there was assumed to be no friction. The material constants were defined on the basis of the previous studies⁷ (Table 1).

An axial force was applied in the longitudinal direction of the miniplate. All simulations were carried out with COSMOS/M ver 1.70 (SRAC, USA). Tensile experiments with a universal testing machine in which strain gauges were attached on a miniplate were made. On the basis of the data, the tensile forces calculated from the peak strain of each case were applied to the loading condition of the analyses. To estimate the bone resorption, the compressive stresses were evaluated.

E. Comparison of stress level between fracture and reconstruction model

In order to compare stress levels of the bone surrounding screws in various situations of osteosynthesis, 3-D finite element models for mandibular fracture and reconstruction using the fibular graft were prepared. Hemimandible and the fibula were simplified to a rectangular prism shaped

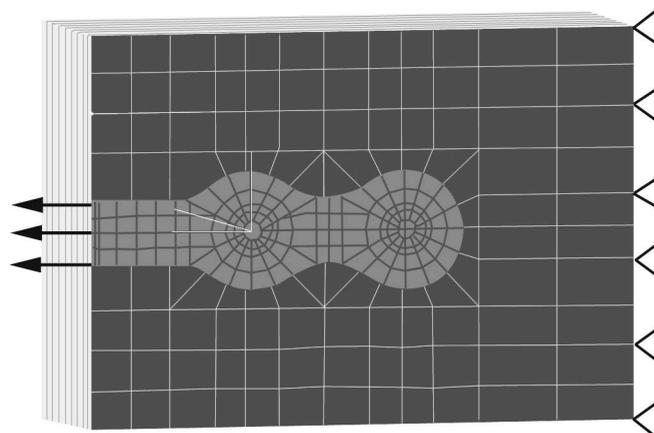


Figure 2. Finite element model for the mandible fixed with a miniplate and screws.

Material	Young's modulus (GPa)	Poisson's ratio
Titanium	110	0.3
Cortical bone	13.7	0.3
Cancellous bone	7.93	0.3

Table 1. Material properties

model. One fracture model and three different types of reconstruction on the left mandible are as follows (Fig. 3). Fracture model: This model was assumed to be fractured in the angle region of the left mandible, fixed with miniplate at the buccal cortical bone 1/3 in height from the upper border. Reconstruction models were simulated for the condition that the fibular graft was transferred for segmental defect from canine to the third molar region.

The models were constructed, taking into consideration the clinical situation; the differences in sizes of the fibula⁸, use of one- or two-miniplate at each osteotomy site⁹, and use of single strut or double barrel fibular graft⁶. Since the fibula is approximately 15 mm height on an average¹⁰, three different sizes were prepared. In these models, the nodes at the inferior border of the mandible were connected to each other.

In order to reproduce the in vivo situation concerning miniplate osteosynthesis under masticatory force, as the similar value of compressive stress would occur in the cortical bone in the fracture model, a vertical force was applied to a point on the antero-superior surface of the cortical bone.

Results

All patients had healed uneventfully judging from the subjective and objective findings, such as occlusal condition, mouth opening and radiographs. The bony fragments at the fracture site were sufficiently united and there was no screw loosening at removal of the miniplates 6 months post-operatively.

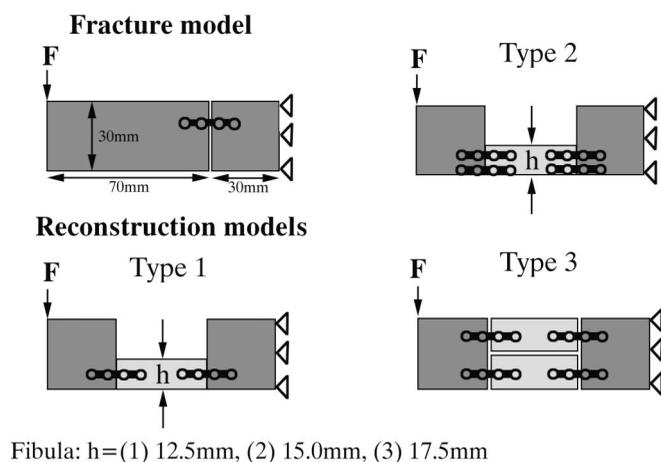


Figure 3. Schematic diagram of a fracture and reconstruction models for finite element analyses.

1. In vivo strains and bite forces

The strains measured in all occlusal points showed tensile strain during the healing period. The values of tensile strain were greater in ipsilateral or contralateral occlusion than those in incisal one. Changes in these strains

showed a monophasic pattern; the strains reached the peak 2 and 4 weeks postoperatively in cases 1, 2, 3 and in case 4, respectively. Since these peak strains were observed, strains had decreased progressively. On the other hand, bite forces had been increasing (Fig. 4).

2. Three-dimensional finite element analyses

The maximum strains of the miniplate (265, 120, 421, 555 μ strain) were converted to tensile forces (74.6, 33.8, 118.6, 156.3 N) using data of tensile experiments. Stress concentrations were observed around the nodes close to the fracture line in each screw. The compressive stress was the most severe at the cortical bone with which the screw neck was in contact. The stress gradually reduced along the length of the screw (Fig. 5). The magnitude of the peak of the minimum principal stress ranged from -8.9 to -41.3 MPa (from -650 to -3000 μ strain) (Fig. 6).

3. Comparison of stress level between fracture and reconstruction models

In all models, the strongest compressive stresses in the cortical bone surrounding screws were observed around the neck of the screw. Compared to the fixation site in reconstruction models, the magnitude of stresses was much greater under the posterior plate (type 1) and the upper plate (type 2 and 3) than that under others, representing similar stress distribution patterns of the fracture model. Therefore, distributions of the compressive stresses of the cortical bone surrounding screws in these sites were evaluated (Fig. 6).

In type 1, the peak stress levels were 2.3 to 3.4 times higher than that in the fracture model, and increased as the height of the fibula decreased. In type 2, there was a reduction in stress levels compared to type 1. The peak stress by use of two miniplates produced stress reduction by approximately 40%, compared to type 1. Distribution patterns, however, had a higher peak of stress by 1.3 - 2.2 times compared to the fracture model. In type 3 (double barrel model), the patterns of stress distributions were quite similar to those in the fracture model and peak stress was the same degree to the fracture model.

Discussion

The present investigation was undertaken to simulate the stress level of the bone surrounding screws in normal healing cases and predict the threshold stress causing bone

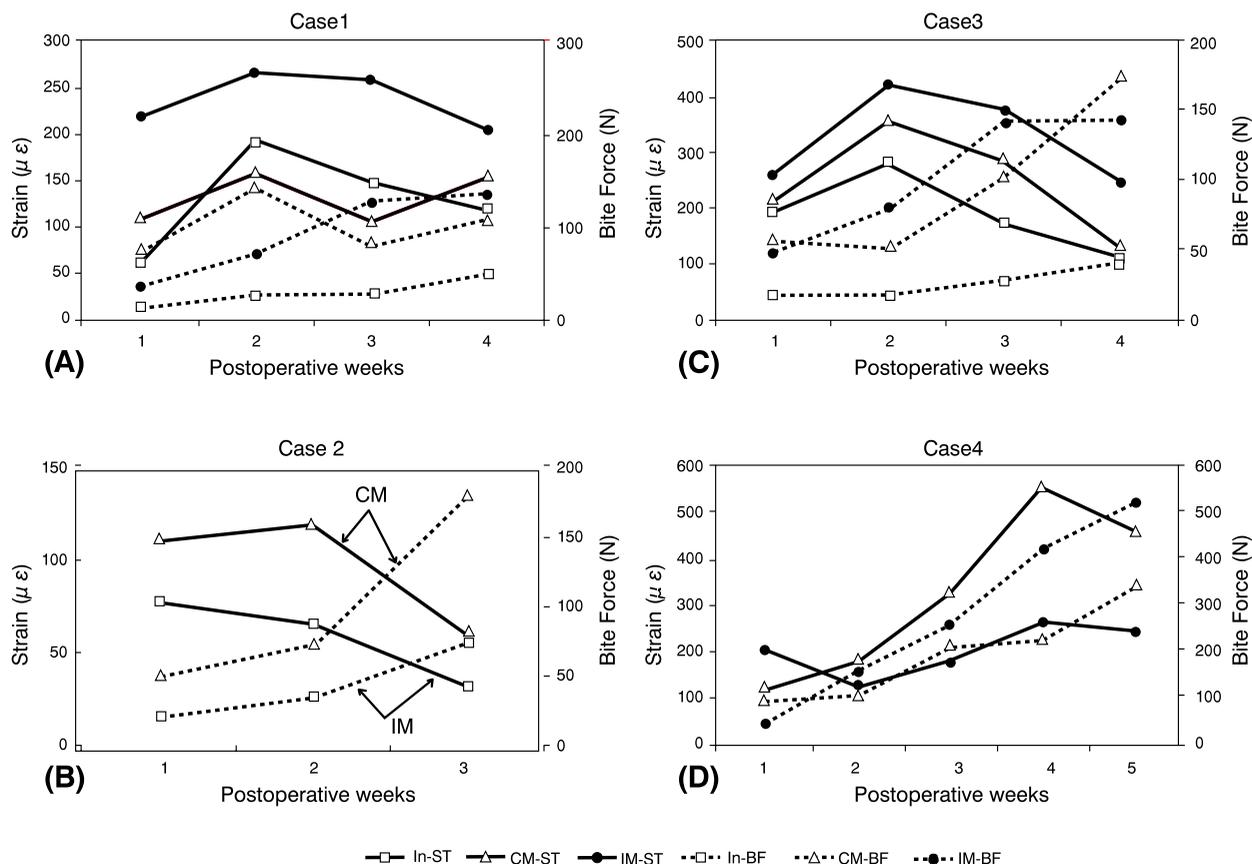


Figure 4. Changes in strains and bite forces. (A) Case 1. (B) Case 2. (C) Case 3. (D) Case 4. In = incisor; IM = ipsilateral molar; CM = contralateral molar; ST = strain; BF = bite force. Real line represents strain; dotted line bite force.

resorption in bone-implant interface during osteosynthesis in vivo. The main finding of our study is that compressive stress within approximately -40MPa would be physiological to the bone and that the critical threshold for bone resorption would be around -50 MPa.

Previously reported studies showed that normal peak physiological strains in adult bones whose main function was load-bearing were about 2500 μ strain in tension and 4000 μ strain in compression^{8,11,12}. The theory of bone remodeling predicts that at very high strains of more than 3000 - 4000 μ strain, bone enters a pathological overload zone, in which

woven bone is added rapidly in response to an immediate need^{9,13}. However, the values of strain reported are derived from deformation of the bone surface of long bone by simplification of bone structure. Internal local stresses in the bone have not been clarified quantitatively. Compared with these experimental and theoretical studies, peak levels of compressive stress (approximately less than 40 MPa, namely less than 2900 μ strain in compression, with 13.7 GPa of Young's modulus of the bone in the calculation) in this study should be in the physiological range where bone formation predominates over bone resorption.

compressive stress

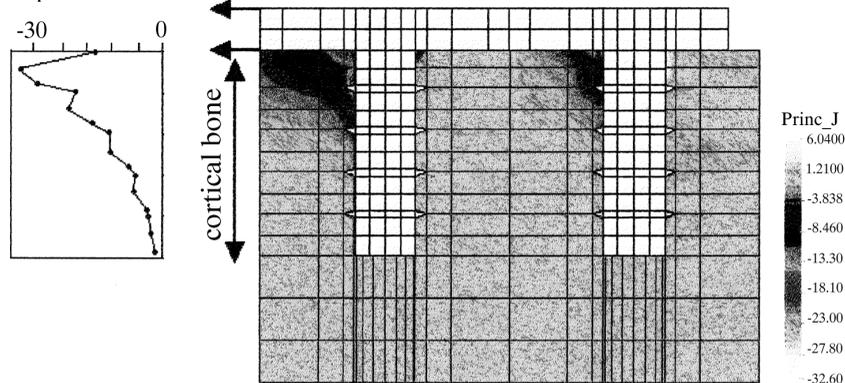


Figure 5. An example of stress distributions in the bone surrounding screws.

With respect to interface stresses, high interface stresses in the immediate postoperative stage have been responsible for bone resorption. In particular, high compressive stresses in the cortical bone are attributed to bone resorption by implant researchers and orthodontists^{14,4,2}. These studies have described stress concentration in the cortical bone surrounding the neck of implants or teeth. Similar stress distribution patterns in bone were found between our fixation model and implant ones. Therefore, this stress or strain level may be applied as the value of physiologically mechanical environment of the cortical bone in these

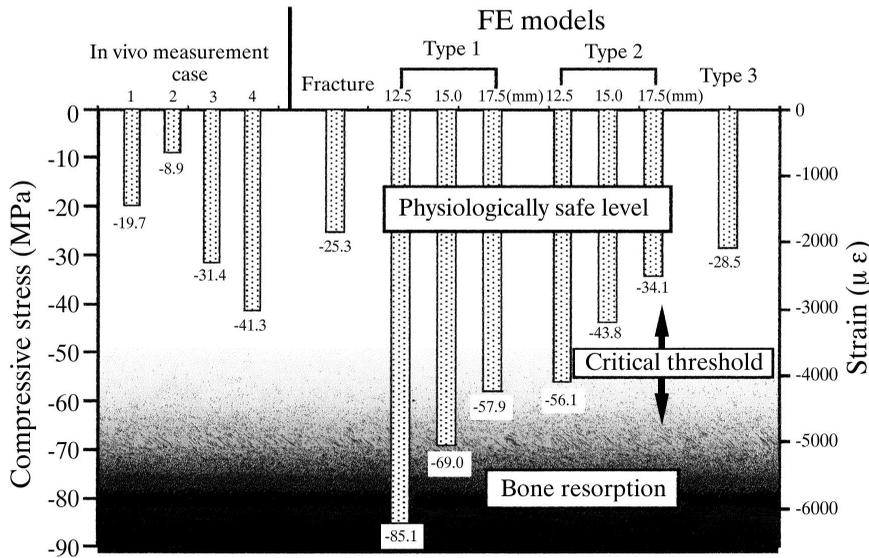


Figure 6. Peak compressive stress in the cortical bone.

simulations. However, absolute value initiating bone resorption has not been established. The fact that many screws had already loosened at the time of removal of the plates⁵ suggests that the threshold stress of bone resorption would be close to the stress occurring during fixation. It also raises the question of how much stresses induce bone resorption around screws in miniplate osteosynthesis.

In our clinical experience, screw loosening was frequent at the rate of 57% (4 out of 7 patients) in mandibular reconstruction using the single strut fibular graft, in particular, with one miniplate at each osteotomy site. In these cases, loosening occurred immediately after surgery at the posterior site of osteosynthesis. These findings show that screw loosening was caused by high stresses, which exceeded the critical threshold for bone resorption in the bone surrounding screws. These experiences led us to use the double barrel fibular grafts, and up to the present, eight patients who have undergone mandibular reconstruction using double strut made good progress.

As for the absolute value of the critical threshold for bone resorption, in cases of mandibular reconstruction using the single strut fibular graft, obviously, the stresses occurring around screws (-57.9 - -85.1 MPa) should be above the threshold. On the other hand, stresses occurring in the bone with double plates (-34.1 - -56.1 MPa) are thought to be somewhat safe in regard to screw loosening¹⁵. Moreover, the maximum compressive stress within -40 MPa has been measured actually, in mandibular fractures. From these observations, we speculated that the critical threshold stress for bone resorption should be approximately -50 MPa (3600 μ strain) (Fig. 6). Factors that affect strains measured in the miniplates are considered to be strength of the callus and bone, loosening of screws, the soft tissue and so on. The rigidity of the callus greatly influences the value of strains more than other factors^{16,17}. With regard to bone stiffness, White et al.¹⁸ reported that fracture healing could be divided into four stages biomechanically. The earliest evidence of

returning strength is seen after 21 to 24 days of healing. This rapid increase in the bone stiffness might be derived from the progressing in endochondral ossification. Our experimental results, except in one case of old fracture, coincide with these findings. Later peak of strains in old fractures could explain the variability in the contact of the bone fragments after surgery, where more callus formation should be required, compared with cases of fresh fracture.

In bone studies, parameters such as magnitude of load, frequency, duration, and so on appear to be important for bone remodeling. The actual stress patterns that occur in the fractured mandible are influenced by several factors that include the osseous anatomy, the forces exerted by the

muscles of mastication, the occlusal loading pattern and the location of fixation appliances. However, it is impossible to know the value of the forces exerted by muscles. Despite the needs for a further study on the quantification of stress level causing bone resorption, the results of this study may provide an important step in quantifying the biomechanically compatible stress.

Conclusion

In conclusion, load-bearing to the miniplate reached the peak two to four weeks postoperatively. Finite element analysis indicates that compressive stress in the cortical bone weaker than approximately -40 MPa would be physiological to the bone. The critical threshold of compressive stress inducing bone resorption should be around -50 MPa (3600 μ strain).

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