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(1) Original Article

(2) The influence of bite force on the internal structure of the mandible through implant

- Three-dimensional and mechanical analysis using micro-CT and finite element method -

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(5) The influence of bite force on the internal structure through implant

(6) anatomy

Abstruct

Applying proper quantity of stress through the teeth is considered essential for maintaining the homeostasis of jaw. The aim of this study is to clarify the effects of the pressure applied via endosseous implants on internal structures of the jaw. A mandible with dental implants for 15 years was analyzed by micro-CT to prepare a finite element model of the mandible including implants and surrounding internal microstructures. Based on this model, mechanical analysis was conducted by the three-dimensional finite element method. The results of the three-dimensional finite element analysis showed that the stress distribution was seen in the trabecular bone around the implants. It became clear that the pressure is transmitted to mandibular internal structures via implants, and stress is dispersed along internal trabecular alignment.

Keywords: trabecular bone/implant/micro-CT/finite element analysis/stress distribution

1. Introduction

Recent studies have clearly shown the effectiveness of endosseous implants as one of the treatment options in the field of prosthodontics.[1,2] Subsequently implants with various shapes and properties are being developed, and procedures and techniques are becoming more diversified. From the standpoint of anatomy, interesting structural changes occur in mandibular trabecular bone due to functional pressure following long-term use of endosseous implants.

Wolff, a German physician, proposed Wolff's Law in 1894, and Huiskes and colleagues documented that functional pressure is responsible for determining bone structure.[3] Several studies have investigated the effects of functional pressure on the jaw and found that reduced functional pressure due to tooth loss was closely involved in resorption of the alveolar bone.[4,5] Therefore, for maintenance of the homeostasis of their internal structures, the pressure application via the teeth is considered essential.[6,7] However, the effects of the pressure via endosseous implants on jaw internal structures have not been clarified. This is because it is difficult to obtain specimens in which endosseous implants have been in place for a long period of time. Hence, in recent years, stress distribution around implants has been assessed by three-dimensional finite element analysis to ascertain stress distribution inside the jaw.[8-10] However, previous studies did not take into account the morphological characteristics of compact bone and cancellous

bone, and as a result, stress distribution inside the jaw with implants remains merely speculative. In order to accurately ascertain stress distribution through jaw microstructures, detailed data of the jaw, including trabecular bone, are needed. Microfocus X-ray CT (hereinafter referred to as micro-CT) is widely used to observe and analyze the internal structure of hard tissue in a non-destructive manner.[11-14] Many studies have used micro-CT to obtain high-resolution images of jaws with implants and have documented high degrees of reproducibility.[15,16] Moreover, three-dimensional finite element models can be prepared based on CT data, and such models can be used in mechanical studies of bone.[17,18]

In the present study, because we had access to a mandible in which endosseous implants had been in place for a long time, the mandible with implants was analyzed by micro-CT and then a model of this and surrounding microstructures was prepared. The aim of this study was to clarify the influence of bite force on the internal structure of the implanted mandible using this model.

2. Materials and Methods

2.1 Sample

The mandible was removed from the cadaver of an 82-year-old man donated for dissection in whom endosseous implants had been in place for fifteen years prior to death. Screw-type 4.2mm implants were placed at the right first and second premolar regions. In addition, the maxilla had a total of six implants from the right canine to third molar regions which were capped with connected crowns. Occlusal contacts were confirmed.

2.2 FE model(Finite element model)

2.2.1 Micro-CT imaging of the mandible

The mandible was scanned using a micro-CT system (HMX-225 Actis4, TESCO, Tokyo, Japan). The system consisted of an imaging device and a computer. The imaging device consisted of an X-ray generator, a 360° rotating stage, and an X-ray detector. During imaging, the specimen was placed on the stage so that the occlusal plane was parallel to the stage surface. The mandible was scanned at the right first and second premolar regions from the upper part of the fixture excluding the abutment to the lower margin of the mandible. (Fig.1) Imaging conditions were as follows : tube voltage 100kV, tube current 70μA, X-ray generator 5μm, and magnification x3.3. An image intensifier (I.I.) was used; this was 4inches in size and had a 1-inch CCD camera with 16-bit 1024x1024 scanning lines. The camera generated 600 raw data images. Based on the raw data, two-dimensional slice data

were prepared by the back projection method. Furthermore, three-dimensional reconstruction was performed using volume rendering, using 600 images.

2.2.2 FE model preparation

Using finite element analysis software (TRI/3D-FEM, Ratoc System Engineering Inc., Tokyo, Japan), meshes were created and stress analysis was carried out. As pretreatment for finite element analysis, three-dimensional data were subjected to noise elimination, down sizing, and binarization based on a threshold value obtained by discrimination analysis. As to the boundary between the mandible and implants, contact areas were considered connected. After labeling, mapping was performed using 8-node hexahedral elements($1voxel=0.05\times 0.05\times 0.05mm^3$) to prepare a finite element model. The cross section of thinnest trabecular bone consisted of at least 10 elements. The total number of nodes and elements was about 550,000 and 750,000, respectively.

2.3 Constitutive laws

The model was constructed from osseous tissue and implants; these were considered linear materials. The mechanical properties of the osseous tissue and implants were set based on published values.[19,20] The Young's modulus and Poisson's ratio for the osseous tissue were 15GPa and 0.30, respectively, while those for the implants were 110GPa and 0.35, respectively. All nodes at the bottom of the mandibular body

were constrained.

2.4 Implant loading

A 500N load was applied to the upper areas of the two implant bodies. The direction of loading was perpendicular to the occlusal plane at loading points.

As to stress distribution, maximum principal stress was analyzed.

3. Results

Figure 2 shows the distribution of principal stress in the sagittal plane. The standard values of principal stress are shown in the lower right corner using a color key. Minus values indicate compression, while plus values indicate tension. White indicates 0MPa, red indicates -10MPa of compressive force, and blue indicates 10MPa of tensile force.

Stress was seen in the cortical bone around the neck of the implants (yellow areas) and compressive stress was concentrated at the tip of the fixtures (yellow-red areas).

Figure 3 shows a three-dimensional image that was cut along the horizontal plane with a thickness of 2.5mm. Stress distribution was confirmed in the trabecular bone surrounding the fixtures (yellow-red areas).

As to stress distribution in the frontal plane near the mental foramen, marked stress distribution was seen in the trabecular bone around the implants, and compressive stress was seen in the osseous wall of the mandibular canal (yellow-red areas) (Figure 4).

4. Discussion

Bone modeling and remodeling mechanisms are said to be controlled by genetic factors and increases and decreases in load.[21,22] Since bone mass decreases with long-term recumbency, neuropathy such as spinal cord injury, or bone and joint immobility due to cast immobilization, it is clear that mechanical stress is essential for normal bone remodeling and bone mass maintenance. The degree of weekly bone mass loss due to inactivity bone atrophy has been reported at around 1% for recumbency and cast immobilization and around 2% for neuropathy, but this degree of bone loss is markedly more than that occurring in postmenopausal osteoporosis, which causes an annual bone loss of around 2-4%.[23]

In the oral cavity, tooth loss causes jawbone resorption. As in inactivity bone atrophy, the cause of resorption is believed to be reduced mechanical stress due to tooth loss. In fact, studies have reported that jawbone mass is affected more by tooth loss than by aging.[4,5,24] Moreover, tooth loss is known to bring about marked changes in trabecular structures inside the jawbone, causing cancellous bone to narrow and lose regularity and connectivity.[6,7] The jawbone is unlike any other bone because mechanical stress is directly transmitted via the teeth, and it is reasonable to assume that teeth have marked effects on jawbone resorption.

Endosseous implants are becoming widespread as a treatment option to replace lost teeth, and these implants are

directly embedded in the jawbone to form a bond known as an osseointegration. Unlike dentures, because the jawbone, implant and superstructure are strongly connected, support and masticatory capabilities should equal those of natural teeth. However, because an implant bonds to the jawbone without the periodontal membrane, there have been some concerns on the effects of implants on the jawbone.[25]

Raadsheer et al. reported that the bite force at the premolar region was 350N in female and 450-580N in male.[26] In the results, the three-dimensional finite element analysis showed that the pressure was transmitted to mandibular internal structures via the implants and that stress was dispersed along internal trabecular alignment. This suggests that when an endosseous implant is placed, mechanical stress is generated in internal trabecular bone to suppress bone resorption due to tooth loss. In this study, higher stress concentration from 5MPa to 10MPa was observed in the trabecular bone around the implants, compared with the result obtained from the mandibular FE model with denture in the previous study. This finding suggests the possibility that the force via implant was related to trabecular bone maintenance.[27]

Furthermore, because stress propagation was dependent on trabecular alignment, stress was likely to concentrate in the osseous tissue around the implants. Stress tends to concentrate in areas where a load is applied, irregular morphological features such as neck and acute angle are present, and elastic

coefficients differ.[28] When an external force is directly applied to the top of an implant, the trabecular bone at the tip of the fixture satisfies all of these conditions, and as a result, stress is likely to concentrate around the implant. Because endosseous implants are placed without periodontal membrane, it is possible that excess stress concentrates in the surrounding jawbone. Therefore, during follow-up visits, dentists need to carefully monitor mechanical stress generated by implants.

Currently, cancellous bone is not often tested before implant placement, but considering that stress concentrates at the tip of a fixture following implant placement, measuring bone density and bone mineral content before implant placement is very important. Furthermore, testing cancellous bone should be useful in determining allowable load. Because trabecular bone realignment around an implant is thought to play an important role in supporting the pressure, it should be a useful test during recall visits in long-term observation after implant placement.

Gross and colleagues reported that when an implant was placed in the mandibular premolar region, neurological symptoms occurred even when the implant was near the mandibular canal but not touching it.[29] They deduced that the neurological symptoms were caused due to stress concentration in the superior wall of the mandibular canal. The results of the present finite element analysis confirmed marked stress concentration in

similar areas. It is therefore necessary to keep in mind that even if an implant does not come in contact with the mandibular canal, when the stress is applied around the mandibular canal after implant placement, stress is distributed to the mandibular canal via internal trabecular bone to cause adverse events such as neurological symptoms.

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Figure legends

Figure 1 3D rendered image of the first and second premolar regions with implants.

Figure 2 Distribution of principal stress in the sagittal plane.

Minus values indicate compression, while plus values indicate tension.

Figure 3 Three-dimensional image that was cut along the horizontal plane with a thickness of 2.5mm.

Figure 4 Stress distribution in the frontal plane.

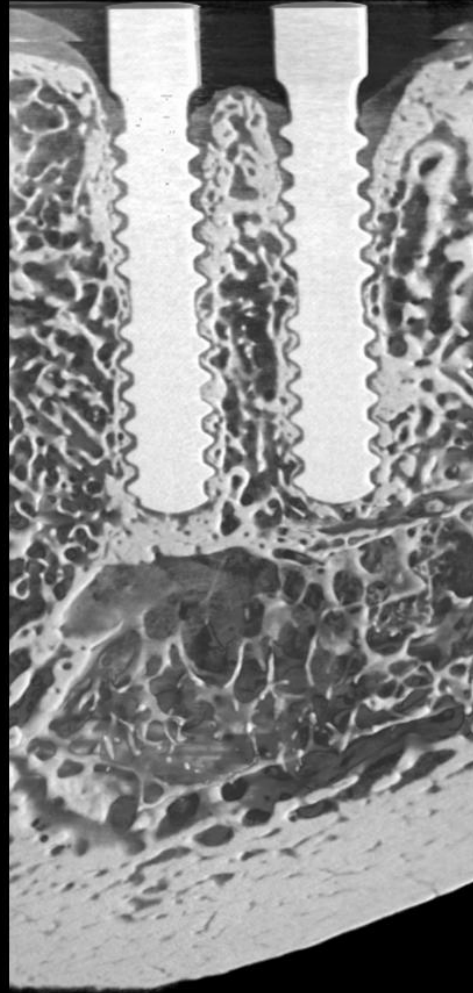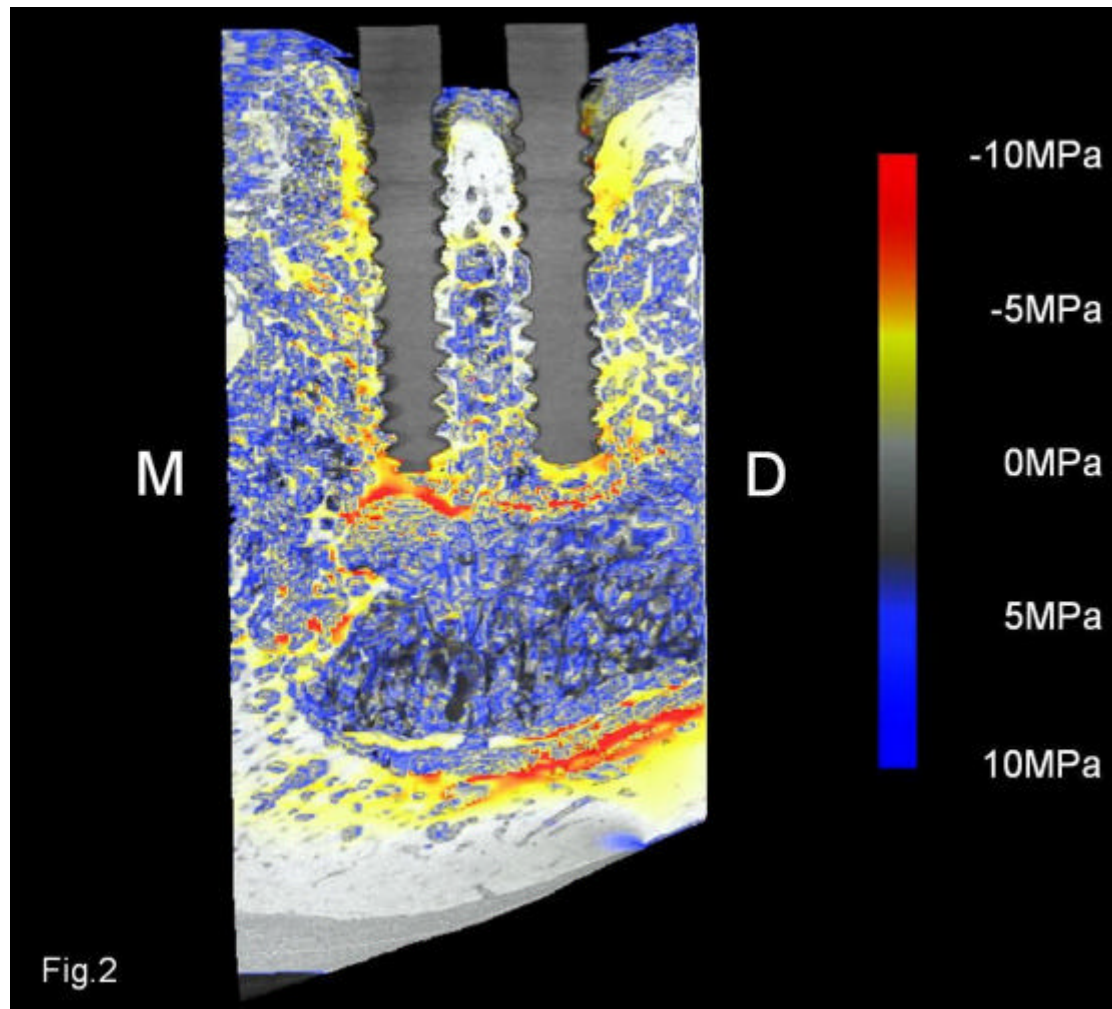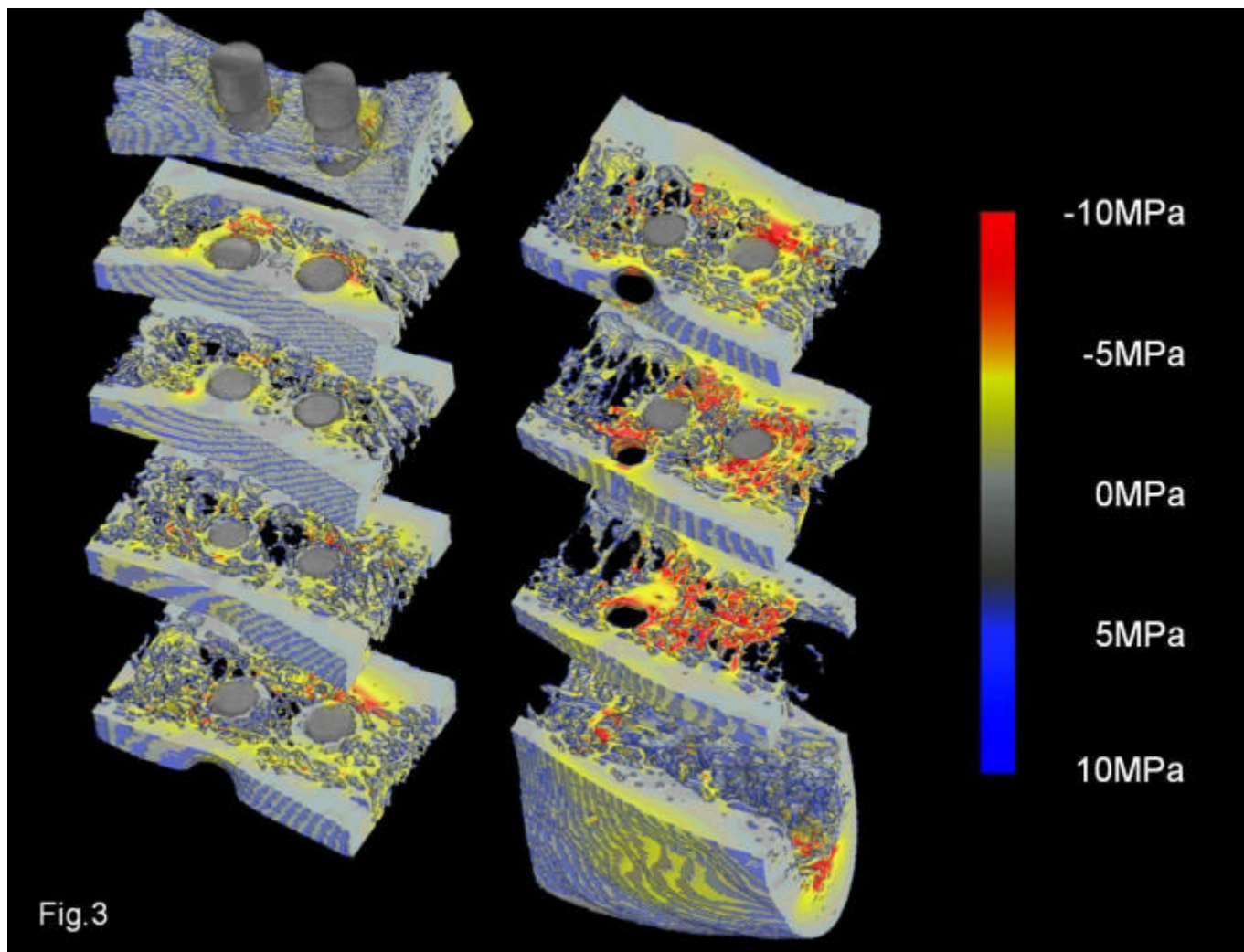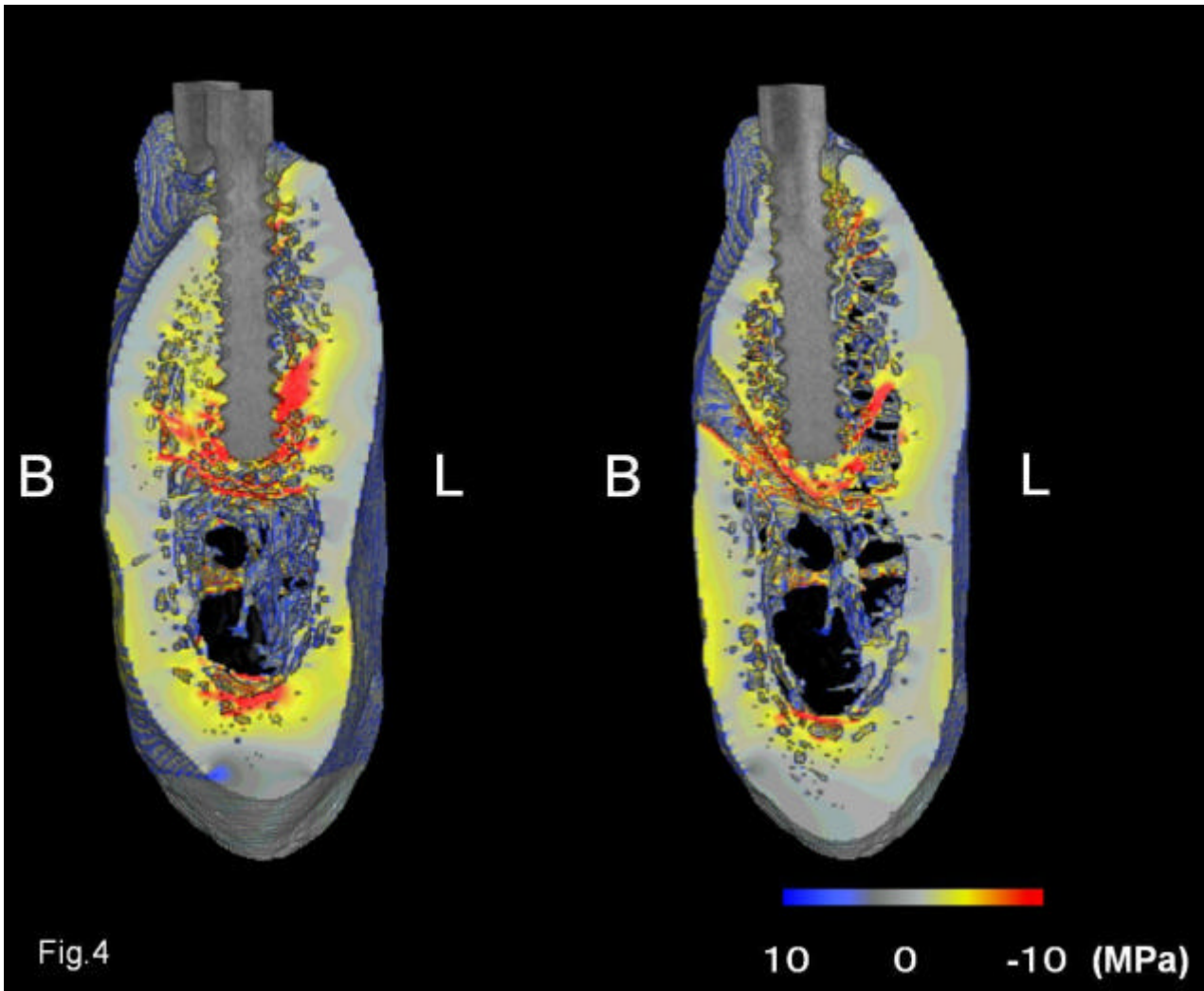(a)First premolar region; (b)Second premolar region.

Fig.1

M   D

-10MPa

-5MPa

0MPa

5MPa

10MPa

Fig.2

Fig.3

-10MPa

-5MPa

0MPa

5MPa

10MPa

B   L   B   L

Fig.4

10   0   -10   (MPa)