Desktop micro-CT image-based dynamic FEM analysis of stress wave pathways between mandibular trabecular bone and cortical bone with comparisons to virtual models with eliminated materials on pathways

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Abstract
To analyze the biomechanical behavior of human bone, micro-CT image-based static FEM analyses considering trabecular architecture have been carried out. In the field of dental biomechanics, not only the static analysis but also dynamic analysis against impact load is required. In this paper, a desktop micro-CT was used for the right half of a human mandible with 0.103 mm resolution after dissecting. The lost information by a saw was recovered by the homogenization model. The impact load was applied to the implant in the molar part and the load transfer from the implant to the cortical bone and trabecular bone was considered. The stress wave pathways from the implant to the condyle were analyzed by comparison with virtual FEM models with eliminated materials on pathways. It was revealed that the stress wave transferred from the implant neck and end part to peri-implant trabecular bone played a significant mechanical role. It was also found that the apparent wave speed in the trabecular bone region was as fast as that in the cortical bone.

Key words: Dental biomechanics, Impact load, Trabecular bone, Micro-CT, FEM, Homogenization method

1. Introduction
The oral implant occupies an important clinical position in the recovery of oral cavity function (Alberktsson, et al., 2008, Greco, et al, 2014) and its use is widespread in many countries. Since the strong correlation between mechanical loading and bone morphology from the microscale to the macroscale is well known, there have been many experimental and numerical studies analyzing the mechanics of the jawbone (Maki, et al., 2003, Kitagawa, et al., 2005, Kim, et al., 2012). In numerical analysis studies, an image-based finite element method (FEM) has been used with the help of X-ray micro-CT or ultrasonic waves. The use of high-resolution images is also becoming popular for three-dimensional modeling of the trabecular microarchitecture.

Most of those numerical studies have solved the static equilibrium problem and have provided new insights into bone remodeling, implant design, and the stability of implants (Sertgöz, et al., 1996, Wang, et al., 2002, Tsubota and Adachi, 2006, Zampelis, et al., 2007, Bergkvist, et al., 2008). With respect to the trabecular bone, while most studies have employed a sort of homogenized material model, direct modeling of the trabecular microarchitecture is now available, even on standard personal computers. Such direct modeling has provided many new findings including the anisotropic characteristics due to the 3D network microarchitecture, which led to discussions of bone quality (Moon, et al., 1997, Limbert, et al., 2010, Frisardi, et al., 2012, Bin Kamisan, et al., 2016).

Under static loading conditions, one author has clarified the mechanical role of the trabecular bone using oral...
implants, focusing on the network structure as a load pathway (Ohashi, et al., 2009) and on the stiffness against shear deformation (Matsunaga, et al., 2013). Whereas the applied load to the jawbone is believed to be supported mainly by the cortical bone, morphology analysis of the trabecular bone by high-resolution image-based FEM analysis has revealed that a well-designed combination of the cortical and trabecular bones actually restrains deformation.

In contrast to the many static FEM analysis, only a few reports have been published on dynamic or impact FEM analysis (Murase, et al., 2007, Garo, et al. 2011, Wagnac, et al., 2012, Basaruddin, et al., 2012, Charef and Serier, 2015), not for jaw bone but for vertebra or other anatomic sites. Therefore, in this study, we conduct an FEM impact analysis using an explicit time-marching algorithm for the right side of the human mandible, consider the trabecular microarchitecture captured by micro-CT, and analyze the stress wave pathways in detail. An impact load was applied to the top of a hypothetically inserted cylindrical FE-model implant to the molar region of a mandible. The stress wave pathways from the impact point to the mandibular condyle via the cortical and trabecular bones are discussed. We conducted some virtual tests in which typical pathways were eliminated materials to clarify the mechanical role of a peri-implant trabecular bone under impact loading. Note that the study was limited to the discussion of a case in which the load was directly applied from the virtually inserted implant to the molar part of the mandibular bone and the transient stress wave pathways from molar part to condyle for a very short time period. One reason for this lies in the difficulty to obtain a dentulous cadaver.

To model the microarchitecture, we used a desktop micro-CT in this study, which required that the mandible be dissected to obtain high-resolution images. Therefore, to reconstruct the 3D model, an asymptotic homogenization method (Lions, 1981, Yoshiwara, et al., 2011) was employed to model the trabecular bone in the region lost because of the saw thickness of 0.3 mm.

2. Material

The subject used in this study is the mandible of a 65-year-old female. After dissecting the right side of mandible by a saw into 4 small parts with 0.3 mm thickness, R1 to R4, as shown in Fig. 1, we used the desktop type micro-CT device (SMX-90CT: Shimadzu, Kyoto, Japan) to obtain three-dimensional models by imaging one part at a time. A voltage of 90 kV and a current of 110 mA were used to scan the specimen. The image resolution and slice interval were both 0.103 mm. The cortical bone, trabecular bone, and marrow were classified by image processing manually. The bone volume fraction in the trabecular bone region measured for each part ranged from 17% to 33%. For the remaining teeth in R4 region, the periodontal ligament was not considered and the teeth itself was ignored. The study protocol was conducted in compliance with the Helsinki Declaration and was approved by the Ethics Committees of Showa University.

3. Modeling and Computational Method

3.1 Reconstruction of full model

The finite element (FE) models were automatically generated using 0.13 mm cubic voxel elements for the cortical
and trabecular bone. The marrow was ignored by assuming the subject to be dry bone, because its viscoelastic properties were hardly obtained. The image-based FEM software VOXELCON (Quint Corporation, Tokyo, Japan) was used for mesh generation and dynamic analysis.

To connect the four separate parts, R1 to R4, in the right half of the mandible, the lost information located in the 0.3mm thick cut layer had to be recovered. It is possible and relatively easy to connect the cortical bone manually. Since the local coordinate system for each part was independent during micro-CT imaging, we removed a very thin amount of the end of each part so that the edge surfaces became perfectly parallel with a 1.0mm gap. As an example, the recovered cortical bone of 1.0mm thickness is shown in yellow color in Fig. 2.

Recovering the lost information of the trabecular network is difficult. The reconstruction of the network architecture was very important in this study, in order to analyze the stress wave propagation. Therefore, we adopted homogenized material modeling technique. After dividing the 1.0mm thick layer into two layers, we filled it with an equivalent homogeneous material model calculated using the neighboring trabecular bone, as shown in Fig. 2. At each end of these parts, we used the 2.0mm thick region as the surrogate microstructure of the lost information. By careful observation of the end layer, we defined the sub-regions. Taking as large representative volume element (RVE) from each sub-region as possible, we applied the asymptotic homogenization method (Lions, 1981) using VOXELCON software. Note that the local coordinate system was defined independently to best characterize each trabecular bone sub-region, then the calculated homogenized elastic tensor was rotated to the global coordinate system.

The reconstructed FE model of the right side of mandible is shown in Fig. 3, which is denoted by the full model F in this paper. Next, as shown in Fig. 3, we inserted a hypothetical implant into the molar part, modeled simply by a 3.0mm diameter cylinder of 12.0mm long. The implant was assumed to be tied to the bone. The condyle was fully constrained in this study. An impact load shown in Fig. 4 was applied to the top of the hypothetical implant.

The Young’s modulus and Poisson ratio of the bone were 10 GPa and 0.4, respectively, in all analyses in this study. The homogenized elastic tensor was used for the recovered trabecular bone region, in which the calculated anisotropic characteristics are included. The hypothetical implant was assumed to have the same Young’s modulus and Poisson ration with titanium, i.e, they were 115.7 GPa and 0.321, respectively. The density of the bone was 1.914x10⁻⁶ kg/mm³,
and that of the implant was $4.54 \times 10^{-6}$ kg/mm$^3$. Note that the R4 part originally had one tooth, which was modeled as bone material for simplicity, since the existence of a tooth did not influence the stress wave pathway from the implant to the condyle in the transient behavior for a very short time period. The marrow was ignored, as described above. Further, viscosity and orthotropy of the bone tissue were also ignored in this study.

### 3.2 Virtual models for investigation of stress wave pathways

In the full model F, schematics of the possible main stress wave pathways from the top of the implant to the mandibular condyle are shown in Fig. 5, which explains that there are three main pathways from implant to surrounding bone: 1) implant neck part to cortical bone, 2) implant neck part to trabecular bone, 3) implant end part to trabecular bone. At the implant neck connected to the top cortical bone, the stress wave may be transferred directly to the cortical bone and also transferred to the peri-implant trabecular bone. After the fast wave propagation in the implant with high stiffness, the compressive stress may be transferred from the implant end to the trabecular bone. Between the cortical and trabecular bones, stress waves from difference sources, which are shown in different colors in Fig. 5, may be transferred.

To investigate the importance of each pathway, we generated three more hypothetical models. The stress wave pathways in red dotted line in Fig. 5 were obstructed in the first model A by eliminating the cortical bone around the implant neck, as shown in Fig. 6(b). In other words, the pathways in only blue and green lines remain in model A.

Next, to obstruct the pathway from implant end to trabecular bone shown in green dashed line in Fig. 5, the second model B was generated by using a short implant, as shown in Fig. 7(b). In the full model F, the implant end was in...
contact with the trabecular bone, which was removed in model B. Hence, the pathways in only red and blue lines remain in model B.

Finally, the third model C had no trabecular bone in R3 part where hypothetical implant was inserted, as shown in Fig. 8. The model C was generated aiming to obstruct both pathways from implant neck and implant end to trabecular bone in blue and green lines, respectively. Note that the stress wave can be transferred to the trabecular bone in the R1, R2, and R4 parts via the cortical bone in model C.

The material properties and boundary conditions in models A to C are the same as in the full model F.

### 3.3 Model for verification of homogenized model of trabecular bone

This section describes a model we developed to numerically verify the accuracy of the homogenized model of the trabecular bone used in the missing cut layer. This model is necessary because the homogenized model in the impact analysis had never been validated. In our numerical verification, R3 part was used as a reference model and we artificially introduced a 0.3mm thick missing layer, as shown in Fig. 9. Then, we filled this layer with the homogenized material model, as shown in Fig. 9(b), in the same way as in the full model F. By using the artificial cut layer, the original R3 model can be used as a reference. The boundary condition is shown in Fig. 9(a), where the same impact load in Fig. 4 was applied to the original tooth part, because the purpose of this analysis lies only in the verification of the homogenized material modeling. We also used the same material properties with the full model F.

![Fig. 9 Model for verification generated from R3 part by introducing artificial missing layer.](image)

### 3.4 Impact analysis method

To analyze the transient behavior up to 50µs, we employed an explicit time marching algorithm and determined an increment time step to satisfy the following Courant condition for numerical stability. This condition ensures that the wave propagation distance in one time step is within one finite element. We estimated the wave propagation speed \( c \) by Eq. (1), where \( K, E, G, \) and \( \rho \) are the bulk modulus, Young’s modulus, shear modulus and density, respectively.

\[
c = \sqrt{\frac{K + \frac{4}{3}G}{\rho}} = \sqrt{\frac{E}{3(1-2v)} + \frac{4}{3}G} \quad \rho
\]

Obviously the wave speed in titanium is faster than that in bone. To this end, a time step of 0.01µs was determined. This impact analysis was carried out by customizing the commercial software VOXELCON 2012.

### 4. Results

#### 4.1 Verification of homogenized model

Before discussing the stress wave propagation in the full model F and virtual models A to D, we first briefly...
present the verification results of the homogenized model. Fig. 10 shows the minimum principal stress contour in the trabecular bone only, which means that the cortical bone is hidden. That for the reference model is shown in Fig. 10(a) and for the verification model in Fig. 10(b). The blue color shows the compressive stress and the red the tensile stress. As shown in Fig. 10(b), since the lower part of the trabecular bone region in the missing layer was blank, no stress was plotted. In the upper half of the replaced homogenized region in the cut layer, the stress discontinuity can be seen. This is because the macroscopic stress value is plotted, which is the average for the porous trabecular bone region and is theoretically lower.

![Figure 10: Comparison of stress wave propagation without and with cut layer](image)

Thereafter, we performed a quantitative comparison between the reference and homogenized models. Figure 11 shows the selection method of regions for quantitative evaluation. We extracted cross-sectional region A, which is closest to the homogenized region, and cross-sectional region B, which is farthest from it. These 2 regions were only extracted from the trabecular bone, and each region consists of a thin section of one voxel in thickness on the yellow line. The results for region A are shown using 4 histograms between 20-50 µs in Fig. 12. The vertical axis shows the value obtained by dividing the number of voxels at each stress value by the total number of voxels in region A. The red line indicates the direct model, blue line indicates the homogenized model, and yellow region shows differences between the 2 models. It was confirmed that, although the difference between them became maximal when the stress wave passed region A at the time of t=20 µs, the difference decreased after the time of t=30 µs. Even in the results for a region B, there were almost no differences between two models in the same way with region A.

To this end, when desktop micro-CT is used for dissected mandible, its full model could be reconstructed using an equivalent homogenized model of trabecular bone.

![Figure 11: Selection method of regions for quantitative evaluation](image)
Fig. 12 Results for region A
The red line: The direct model
The blue line: The homogenized model

4.2 Stress wave propagation

Fig. 13 shows the buccal and lingual side views for the full model F from 10 µs after impact through 50 µs. At time 10 µs, the pathway from implant neck to cortical bone is observed in buccal side view that was illustrated as red dotted arrow in Fig. 5. Also, the pathway from implant end to cortical bone via trabecular bone can be seen in lingual side view that was illustrated as blue dashed arrow in Fig. 5. After that, the stress wave propagated almost concentrically around the implant. As verified in the previous section, we observed no singular behavior when the stress wave passed through the homogenized material layers. At time 50 µs, the stress wave reached condyle.

The model A results are shown in Fig. 14, where we observed no stress wave propagation from the implant neck to the cortical bone in both buccal and lingual side views at time 10 µs. In the lingual side view, only the pathway from implant end can be observed. However, carefully watching the isopleths in the principal stress contour, subsequent behavior up to 50 µs was very similar to that observed in the full model F especially when the stress wave reached condyle at 50 µs.

The model B results are shown in Fig. 15, where no pathway from implant neck was observed in lingual side view at 10 µs. The differences between models F and A were observed clearly until 30 µs, and slightly at 50 µs as well.

The model C results are shown in Fig. 16, in which we observed almost no stress transfer from the implant end in the lingual side view at 10 µs. Even the stress transfer near the implant neck was less than that in model B. This implies the pathway from implant neck to trabecular bone and finally to cortical bone exists. Subsequent behavior is totally different from other models, F, A and B until 50 µs. Hence, contribution of the trabecular bone to the stress wave propagation to condyle is not negligible.
To understand further the mechanical role of the trabecular bone, the stresses in the trabecular bone are compared among models F, A, B, and C in Figs. 17 and 18. Again, we observed the above mentioned points of differences. Also, by comparison with Figs. 14 to 16, it was revealed that the stress wave propagated in the trabecular bone at almost the same speed as in the cortical bone, due to the cross transfer between cortical bone and trabecular bone.

5. Discussion

The numerical results of the full model F and the three virtual models showed different stress wave propagation with respect to both the peri-implant pathways and the distant-implant pathways. The findings were summarized in Fig. 19. The line width shows the significance to the stress wave propagation to the condyle part.
Fig. 18 Lingual side view of minimum principal stress contour in trabecular bone.

Fig. 19 Stress wave pathways in full model F. The line width shows significance of pathways.

The pathways from the implant neck and from the implant end to the peri-implant trabecular bone play an important transient behavioral role. However, the direct pathway from the implant neck to the cortical bone did not influence the global behavior much. In the static analysis, the tight connection between the implant neck and the top cortical bone is significant in supporting the load from the implant. The thickness of the top cortical bone is important for the stability of the implant. However, the peri-implant top cortical bone was not significant with respect to the transient behavior in the very short period of the impact load. We also found the pathway from the implant end to the trabecular bone to significantly influence the global behavior.

Another finding relates to the wave propagation speed in the trabecular bone. Theoretically, it was estimated to be slower than that in the dense cortical bone, because the apparent density of the trabecular bone is proportional to the bone volume fraction, but the apparent Young’s modulus is lower than the linear rule of mixtures. However, the stress wave propagated at almost the same speed as in the cortical bone. The reason for this may be the very complicated cross transfer of the stress wave between the cortical bone and the trabecular bone. Finally, the existence of the trabecular bone significantly influenced the global behavior of the mandible against impact.

Concerning the homogenized material model, we verified its application to the thin missing cut layers, even with respect to impact problems. When using the homogenized material model, however, the pathways between the trabecular bone and the cortical bone were not correctly modeled. Therefore, the use of the homogenized model should be limited to small regions as in this study.

Regarding future work, a consideration of marrow is indispensable. Moreover, a comparison between static and impact analyses for a whole mandible model will clarify the differences. Furthermore, a dynamic analysis of the whole mandibular model during mastication may show the importance of the trabecular bone during mandibular movement, and reveal the relationship between the growth direction of the mandibular bone and the trabeculae.
In addition, only one case was analyzed in the present study. Actually, there is a possibility that the stress wave propagation speed and trabecular bone may be dependent on the individual characteristics of subjects. In this study, a method to calculate the stress wave propagation was established. In the future, we would like to analyze multiple subjects using this method, statistically analyze the results, and discuss the influence of differences among individuals.

Finally, the limitations of this study were the unrealistic constraint conditions and the neglect of marrow, muscle and periodontal ligament. We consider that viscosity and orthotropy influence the results. But, viscosity and orthotropy of the bone tissue were also ignored in this study. Unfortunately, because the present study used explicit time marching, it is suitable for a short time, but is not suitable for a long time. In addition, the results of this study are qualitative, and validation should be performed.

6. Conclusion

In this study, we solved the impact problem by a micro-CT image-based FEM for the right half of a human mandible. The trabecular architecture was reconstructed from 0.103 mm resolution images. Using a desktop type micro-CT device, the subject was sawed into nine parts. The lost information of the 0.3 mm thick cut layer was recovered using an asymptotic homogenization method in the trabecular bone region. First, we verified the use of the homogenized material model in the impact analysis. Next, we studied the stress wave pathways up to 50 µs for a full model and three virtual models in which some pathways were obstructed. The results reveal that the impact shock applied to the top of the implant was transferred to the peri-implant cortical bone and trabecular bone from the implant neck and implant end. The stress wave transferred from the implant neck played a significant mechanical role, and the cross transfer of the stress wave between the cortical bone and the trabecular bone was revealed. We also found that the apparent wave speed in the trabecular bone region was as fast as that in the cortical bone.

The limitations of this study were the unrealistic constraint conditions and the neglect of marrow and muscle. In addition, the results of this study are qualitative, and validation should be performed.

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