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3차원 유한요소법을 이용한 골절판에 대한 인체 대퇴골의 골재형성에 관한 연구

김 현 수

= Abstract =

A Study on the Prediction of Bone Remodeling of Plated-Human Femur using 3-Dimensional Finite Element Method

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The stress distribution of bone is altered by the rigid bone plate, sometimes resulting in unfavorable osteoporosis. The rigidity and the biocompatibility are important factors for the design of prosthesis.

However, it is also necessary to consider the effect on the bone remodeling. In this paper, it is attempted to establish an approximate and simple method to predict the trend of the configuration of surface bone remodeling for the case of a bone plate using stress analysis. Thus, three dimensional finite element model of plated-human femur is generated and simulated. In addition. the stress difference method(SDM) is introduced and attempted to demonstrate the configuration of surface bone remodeling of the plated-human femur. The results are compared with those of *in-vivo* tests and the feasibility of the stress difference method is discussed.

Key Words : osteoporosis, prosthesis, biocompatibility, bone remodeling

1. INTRODUCTION

In general, the biocompatibility of the material and the rigidity of the prosthesis itself has been considered to be the most important factors for the design of various prostheses. Bone, however, is one of the dynamic structure. Its mechanical properties and configuration change with time due to the prosthesis. Thus, it sometimes occurs that the bone just in contact with the prosthesis becomes weaker compared with the normal bone since much of the physiological load transfers through the rigid prosthesis rather than through the bone.

It is well documented that the rigid bone plate could induce osteopenia beneath the bone plate (Woo, Akeson, Coutts, Rutherford, Doty, Jemmott, Amiel, 1976, Akeson, Woo, Coutts, Mattews, Gonsalves, Amiel, 1975, Carter, Vasu,

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Harris, 1981). The rigid fixation favors primary bone healing, however, the mechanical stress shielding during the later stages of healing may lead to osteoporosis with decreased bone strength. Thus, refracture could happen to the healed bone(Hidaka, Gustilo, 1984, Uhthoff, Dubuc, 1971, Tonino, Davidson, Klopper, Linclau, 1976).

Recently, numerous researrches are attempted to develop a new bone plate to eliminate this side effect(Hutzschenreuter, Mathys, Walk, Brummer, 1980, Claes, Burri, Kinzl, Fitzer, Hutter, 1980, Cocoran, Koroluk, Parsons, Alexander, Weiss, 1980, Zimmerman, Parsons. Alexander, 1987, Tomita, Kutsuna, 1987).

Generally, in the plated cortical bone, endosteal or periosteal resorption was observed, resulting in cortical thinning. However, it is not clear whether the resorption occurs at the endosteal or periosteal site of the bone. Uhthoff and Dubuc performed 24-week canine experiments to search for the reason for healed bone refracture after plate removal. They reported that the reduction of the shaft caliber is caused by periosteal resorption, which was shown by tetracycline fluorescence technique and histology(Uhthoff, Dubuc, 1971). On the other hand, Tonino et al. pronounced that the significant decrease in bone mineral mass and in mechanical properties was due to massive endosteal resorption (Tonino, Davidson, Klopper, Linclau, 1976). In addition, Akeson et al, and Moyen et al. also showed that the cortical thinning, from the enlargement of the medullary cavity, is also predominantly due to endosteal resorption, supporting the results of Tonino and associates(Akeson, Woo, Rutherford, Coutts, Gonsalves, Amiel, 1976, Moyen, Lahey, Weinberg, Harris, 1978). The previous results suggest that the alteration of the state of stress in the bone, upon the implantation of a bone plate, causes an adaptive bone remodeling response(endosteal or periosteal resorption).

Although it has proper biocompatibility and strength, it may not be a good prosthesis if it could induce undesirable bone remodeling.

Therefore, an attempt is made to ascertain whether this observed adaptive surface bone remodeling upon the alteration of loading conditions can be demonstrated using only the local stress difference between the intact and implanted bone. This is based on the idea that the amount of bone remodeling is related with the stress difference(Huiskes, Nunamaker, 1984, Kummer, 1972).

In order to perform the stress analysis, three dimensional finite element models of human plated-femur and non-plated femur are generated. The stress difference of the same spot between these two models is used to predict the amount of bone remodeling. The feasibility of the stress differecne method(SDM) attempted in this research for the prediction of bone remodeling is discussed by the comparision with the results of *in-vivo* tests.

2. BACKGROUND

Pauwels(1965) attempted to develop a qualitative theory on the functional adaptation of bone. His hypothesis was based on the observation that the over-use of an organ leads to a hypertropy, on the condition that the forces remain within certain physiological limits, and that non-use is followed by atrophy. He described the relationship between bone remodeling and stress with Eqn. (1) and assumed that the bone is homogeneous with respect to its me chanical properties(Huiskes, Nunamaker. 1984).

$$U=f((\sigma-\sigma_s)^n) \quad (1)$$

where, U : bone remodeling(positive : bone apposition, negative : bone resorption)
σ : actual stress in the bone
σ_s : optimal stress(remodeling equilibrium)-
n : an exponent
f : function.

Kummer(1972) attempted to develop a mathematical model to approximate the qualitative observations made by Pauwels on bone remodeling. He suggested an approximation to the observed reactions could be made by Eqn. (2) in which bone remodeling is expressed as a third degree function in stress.

$$U=a((\sigma_s-\sigma_u)^2(\sigma_i-\sigma_s)-(\sigma_i-\sigma_s)^3) \quad (2)$$

where, U : bone remodeling
a : factor of proportionality, related to the speed of remodeling
σ_s : optimal stress at which the remodeling is in balance
σ_u : lowest stress of the bone tolerence
σ_i : actual stress.

Kummer's cubic equation enables one to simulate the behavior of bone using a computer. However, three kinds of adaptive remodeling processes can be generated, depending on the value of factor a. Figure 1 (a), (b) and (c) show the differences in remodeling "damping" provided by different choices for the a value. Moreover, the model is based on the stress magnitude only. It does not specify the component nor the sign of the stress, which have been shown to be important in the remodeling process(Kummer, 1972).

The stress difference method attempted in this paper is also based on the stress. SDM is one method just to qualitatively predict surface bone remodeling. It is based on the following assumption. First, the remodeling in the intact femur is not considered. Thus, it is used as the reference condition of the remodeling for comparison. Second, the amount of the surface bone remodeling is purely proportional to the difference of the local stresses between the intact and implanted bone. Bone formation occurs when the differences in the stresses are increased, while bone resorption occurs when the differences in the stresses are decreased. This is expressed in Eqn(3).

$$U^*=C^*(\,|\sigma_{int}|-|\sigma_{imp}|\,) \quad (3)$$

where, U^* : the amount of the surface bone remodeling

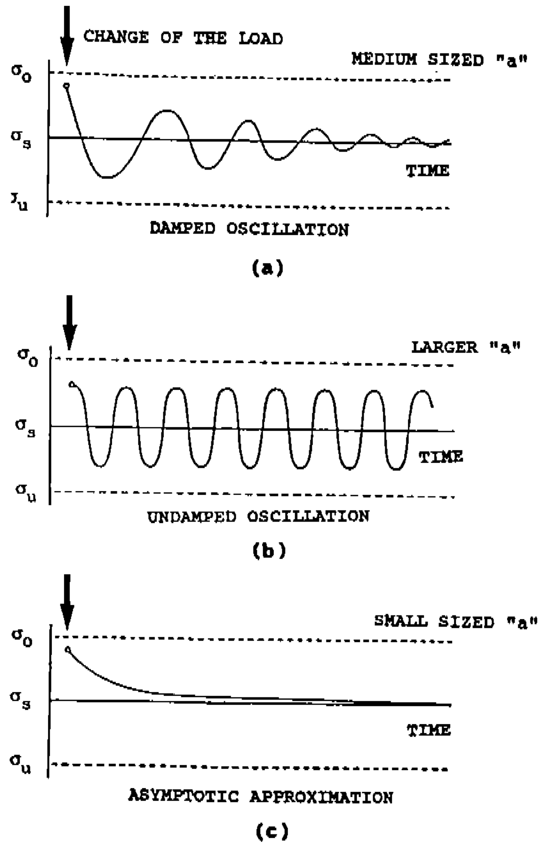

Fig. 1 Three types of computer remodeling processes dependent of the factor of proportionality(from Kummer, 1972).

C^* : the proportionality constant

σ_{int} : the stress of intact femur

σ_{imp} : the stress of implanted femur

Finally, the proportionality constant C^* is an arbitrary time dependent constant. As shown in equation 3, bone remodeling is related to the choice of this constant. Arbitrary constants C^* can be chosen to demonstrate the bone remodeling properly and to represent a decreasing trend in bone remodeling as time passes.

3. FINITE ELEMENT METHOD AND RESULTS

The finite element model simulated for the prediction of surface bone remodeling is shown in figure 2. It was obtained by modifying the FEM model used in the previous study(Kim, 1991) The model includes a rigid conventional plate, represented as a simple plate without the bone screws for simplicity. It was represented with 8-node isoparametric elements, and each node had three degrees of freedom. The model consists of 1090 nodes and 572 elements. the material properties are given in Table 1. The cortical bone is assumed transversely isotropic, and the elastic constants determined by Ashman et al. are adopted for the material property of the cortical bone(Ashman, Cowin, Van Buskirk, Rice, 1984). For the loading conditions, the analysis performed by McLeish and Charnley has been adopted, who investigated the essential muscle forces for the state of slow-walking(McLeish, Charnley, 1970).

The section numbers of the finite element model are shown in Figure 3 and the results of the simulation of the surface bone remodeling due to plate implantation are shown in figures 5-9. The original section means the cross section of the intact femur. The time interval for the prediction is one year and the prediction is per-

Table 1 The material properties

	Cortical bone		Cancellous bone	Plate
Young's modulus (GPa)	E_1	11.5	0.325	200
	E_2	11.5		
	E_3	17.0		
Poisson's ratio	ν_1	0.3	0.29	0.3
	ν_2	0.35		
	ν_3	0.35		

The subscripts : 1 ; Radial direction
2 ; Circumferential direction
3 ; Longitudinal direction

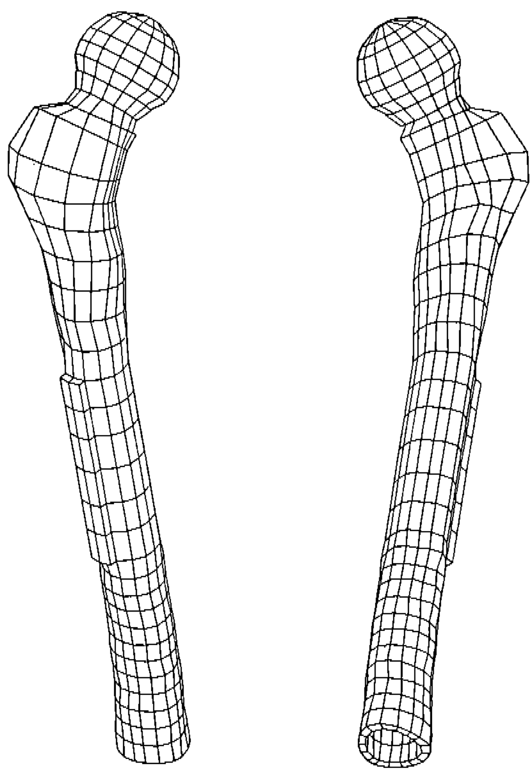

Fig. 2 The finite element model of the implanted human femur for the surface bone remodeling simulation.

formed up to two years. In general, the bone plate is removed depending on the healing state of patient.

Thus, the simulation period of two year may be too long and unreasonable, However, for the purpose of demonstration, the simulation is attempted up to 2 years.

The stress of unplated region of the intact model and plated model is almost the same. Therefore, the amount of bone remodeling is negligible for the unplated region. However, cortical bone thinning is much more evident for the plated regions (section #14, #15, #16, #17, and #18). They are shown in Figures 5-9.

In order to investigate the trend of bone remodeling, the normal stress of bone elements of section #14, #15, and #16 is shown in Table 2. In these sections, much more bone remodeling occurs than any other sections. The configuration of section #14, #15, #16 and the element number is shown in Figure 4.

Table 2 The normal stress of bone elements of section #14, #15, #16(unit : MPa)

elem. No.	intact	sec. #14	intact	sec. #15	intact	sec. #16
1	15.02	1.83	15.60	1.05	16.19	0.97
2	9.60	2.34	9.64	0.91	9.83	0.55
3	1.82	1.34	1.44	-1.05	1.20	-1.56
4	-5.94	-1.33	-6.50	-4.07	-7.11	-4.61
5	-13.56	-5.29	-14.40	-6.96	-15.33	-7.77
6	-18.76	-8.52	-19.79	-8.79	-20.94	-10.66
7	-19.99	-13.38	-20.92	-12.38	-22.03	-13.39
8	-19.54	-17.29	-20.33	-15.55	-21.29	-15.03
9	-17.80	-18.60	-18.27	-16.77	-18.95	-16.06
10	-14.33	-16.00	-14.51	-15.02	-14.80	-15.60
11	-9.18	-12.04	-9.05	-12.51	-8.85	-14.22
12	-2.27	-10.23	-1.89	-11.87	-1.20	-12.41
13	3.99	-6.96	4.67	-9.37	5.63	-9.46
14	9.32	-4.46	10.29	-6.31	11.33	-6.28
15	14.43	-2.02	15.53	-3.08	16.54	-2.94
16	16.81	0.44	17.19	-0.29	18.66	-0.15

Note that in general, the resorption in the plated region (lateral side) is larger than that of the medial side and it occurs in both the endosteal and periosteal sides. Furthermore, more resorption occurred in the endosteal side than in the periosteal side. However, for the medial side the trend of bone remodeling is reversed. More bone remodeling occurs in the per-

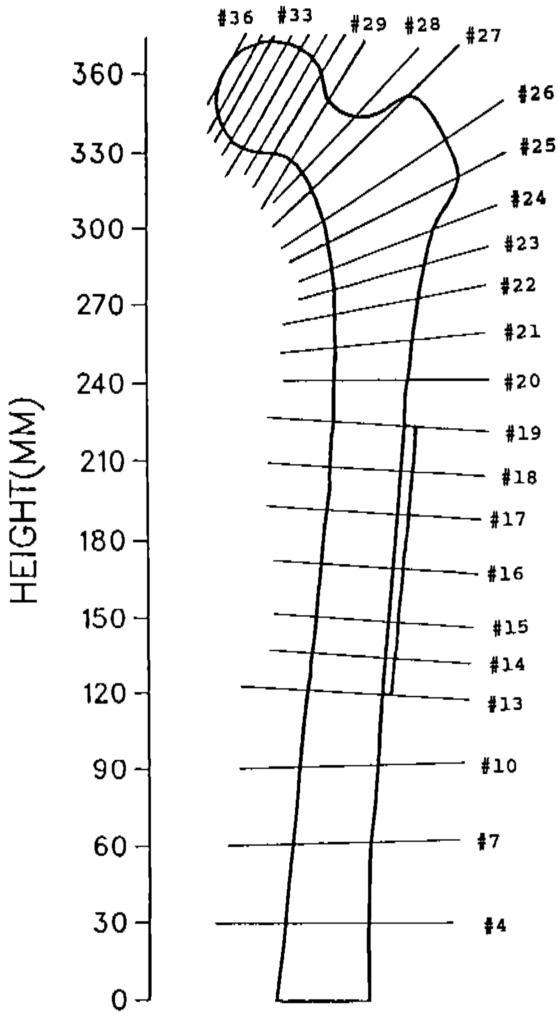

Fig. 3 Section lines of the implanted human femur for three dimensional FEM model.

iosteal side than in the endosteal side. In addition., nearer the mid section of the plate (sections #15, #16 and #17) more resorption occurs than at the outer sections of the plate (sections #14 and #18).

4. DISCUSSION

The prediction of the surface remodeling was attempted by the use of stress difference method. The results showed that remodeling occurs both at the periosteal and endosteal sites simultaneously. No significant remodeling was shown for the unplated region, while cortical thinning was much more evident for the plated section.

More resorption occurs at the endosteal than at the periosteal site for the plated region, which may support the results of Tonino et al.

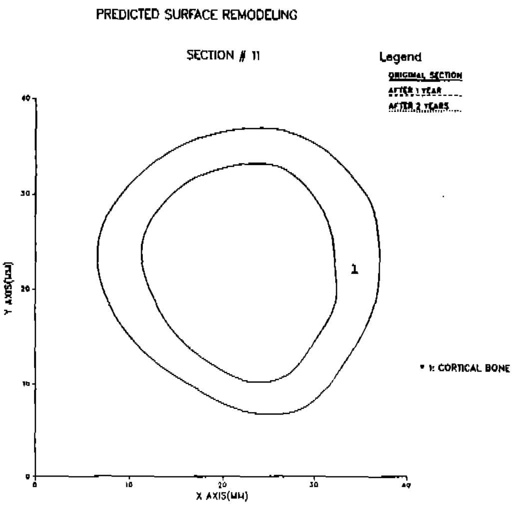

Fig. 4 Element number of section #14, #15 and #16.

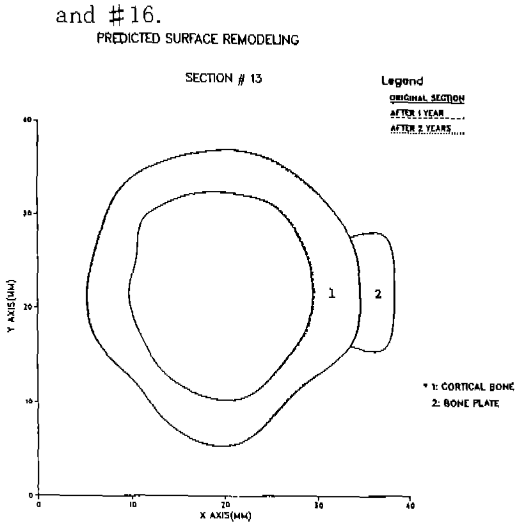

Fig. 5 Predicted surface remodeling of the implanted human femur at section #14 (unit : mm)

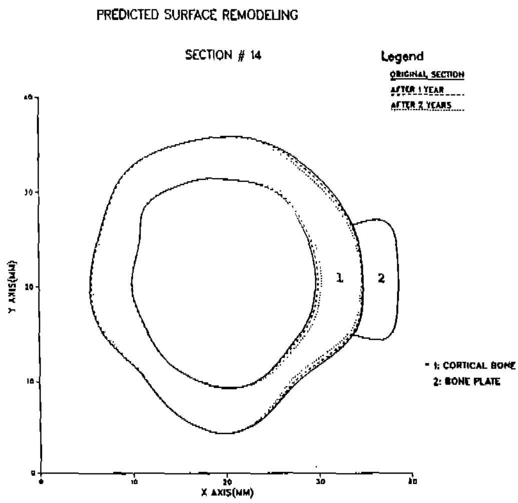

Fig. 6 Predicted surface remodeling of the implanted human femur at section #15 (unit : mm)

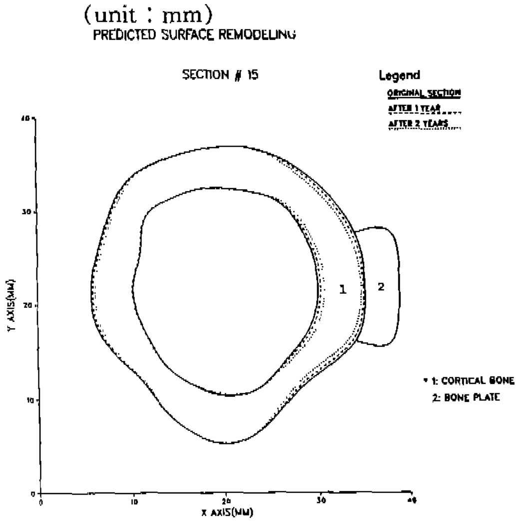

Fig. 7 Predicted surface remodeling of the implanted human femur at section #16 (unit : mm)

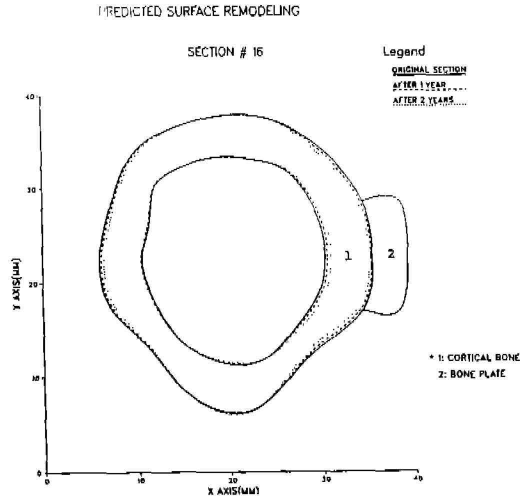

Fig. 8 Predicted surface remodeling of the implanted human femur at section #17 (unit : mm)

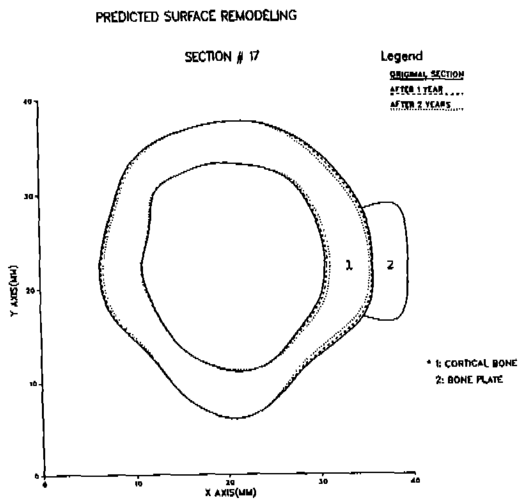

Fig. 9 Predicted surface remodeling of the implanted human femur at section #18 (unit : mm)

(1976), Akeson et al.(1976), Moyen et al. (1978). However, for the opposite site the trend is somewhat different. Thus, it is inferred that the enlargement of the medullary canal is predominantly caused by the endosteal resorption of the lateral side.

more bone resorption takes place at the inner plated region(sections #15, #16 and #17) than at the outer plated region(sections #14 and #18). This suggests that more stress shielding occurs at the inner plated region than at the outer plated region. This trend is also supported by the stress analysis performed in the previous study(Kim, 1991).

The stress difference method attempted in this study is not a sophisticated quantitative method for describing surface bone remodeling, however, the results suggest that it could be a reasonable approximate method for the prediction of trends in surface bone remodeling. It is also able to demonstrate the relative cortical thickness changes at every location, and it can indicate the regions where significant stress shielding occurs.

5. CONCLUSIONS

The stress difference method was attempted to predict surface bone remodeling. In order to ascertain whether the result of the SDM is consistent with the experimental evidence, a human femur, implanted with a conventional plate was simulated. From the results, the following conclusions can be drawn :

(1) The SDM can describe the general trend of surface bone remodeling observed *in-vivo* tests.

(2) The relative surface bone remodeling of each location in the bone can be demonstrated by the use of the SDM.

(3) The SDM can indicate the regions where significant stress shielding occurs.

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