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A Study on the Prediction of Bone Remodeling of Plated-Human Femur using Stress Analysis

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Abstract

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 upon 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.

1. INTRODUCTION

In general, the biocompatibility of the material and the rigidity of the prosthesis itself have 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 rigider prosthesis rather than the bone.

Itl is well documented that the rigid bone plate can introduce osteopenia beneath the bone plate [1-3]. 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 [4-6]. These days, many researches are attempted to develop a new bone plate to eliminate this side effect [7-11].

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 refracture of healed bone after plate removal.

They reported that the reduction of the shaft caliber is caused by periosteal resorption, which was shown by tetracycline fluorescene technique and histology [5]. 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 [6]. 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 [1, 12]. 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).

It may not be a good prosthesis if it could induce undesirable bone remolding although it has proper biocompatibility and strength.

Therefore, an attempt is made to ascertain whether this observed adaptive surface bone remolding 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 [13, 14].

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 difference method [SDM] attempted in this research for the prediction of bone remodeling is discussed by the comparison with the results of in-vivo tests.

2. Background

Pauwels (1965) attempted to develop a qualitative theory on the functional adaption of bone. His hypothesis was based on the observation that the over-use of an organ leads to a hypertrophy, 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 equation 1 and assumed that the bone is homogeneous with respect to its mechanical properties [13].

$$U=f((\sigma-\sigma_S)^n) \cdots\cdots (1)$$

where U : bone remodeling (positive : bone apposition, negative : bone resorption)sigma : actual stress (remodeling equilibrium)

σ : actual stress (remodeling equilibrium)

σ_s : optimal stess (remodeling equilibrium)

n : function

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

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

where U : *bone remodeling*

a : factor of proportionality, related to the speed of remodeling

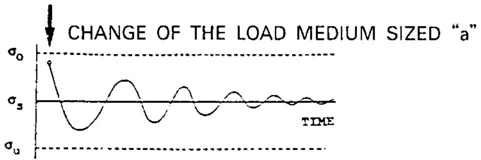
σ_s : optimal stress at which the remodeling is in balance

σ_u : lowest stress of the bone tolerance

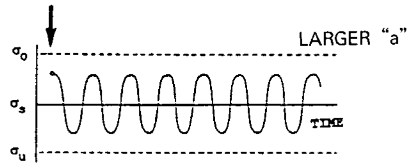
σ_i : actual stress

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 [14].

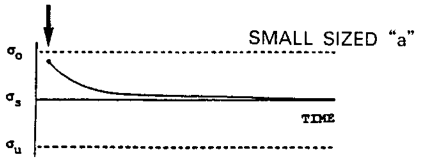
The stress difference method attempted in this paper is also based on the stress. SDM is one method just to qualitatively predict surface bone remodeling. It is based on the following assumptions. First, the remodeling in the intact femur is not considered. Thus, it is used as the reference condition 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 equation 3.



DAMPED OSCILLATION
(a)



UNDAMPED OSCILLATTON
(b)



ASYMPTOTIC APPROXIMATION
(c)

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

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

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

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 constant 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 [15]. 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 [16]. For the loading conditions, the analysis performed by Mcleish and Charnley has been adopted [17]. The results of surface bone remodeling due to plate implantation are shown in Figures 4~20. The section numbers are shown in Figure 3. The original section means the cross section of the intact femur. The time interval for the predictions is one year and the prediction is performed up to two years. In Figures 4~8, 16~20, no distinguishable surface remodeling was exhibited. Since they represent all of the unplated regions (sections #3, #5, #7, #9, #11 and #20,), unnoticeable differences in the stresses between the intact and the implanted casesl were observed.

However, cortical bone thinning is much more evident for the plated regions (section #13, #14, #15, #16, #17, #18 and #19). They are shown in Figures 9~15. 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 the bone remodeling is reversed. More bone remodeling occurs in the periosteal side than in the endosteal side. In addition, nearer the mid section of the plate (sections #14, #15, #16, and #17) more resorption occurs than at the outer sections of the plate (sections #13, *18, and *19).

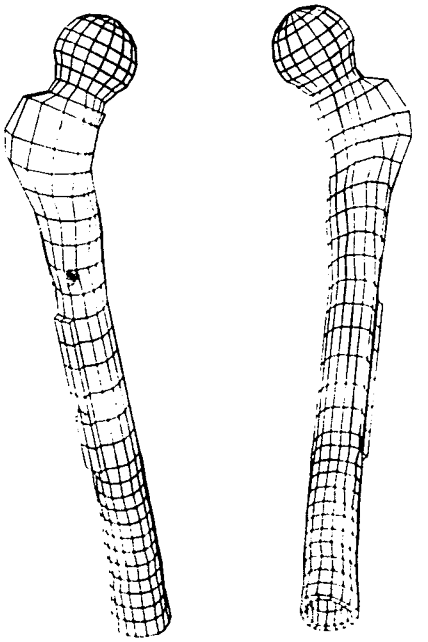


Figure 2
The finite element model of the implanted human femur for the surface bone re-modeling simulation

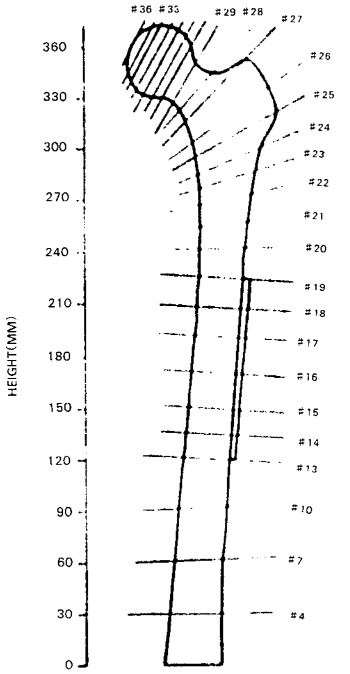


Figure 3
Section lines of the implanted human femur for three dimensional FEM model

Table 1. Material properties

	Cortical bone		Cancellous bone	Plate & Screw
Young′ s modulus (GPa)	E_1	11.5	0.325	200
	E_2	11.5		
	E_3	17.0		
Poisson′ s ratio	υ_{12}	0.3	0.29	0.3
	υ_{13}	0.29		
	υ_{13}	0.35		

The subscripts : 1;radial direction
2;circumferential direction
3;longitudinal direction

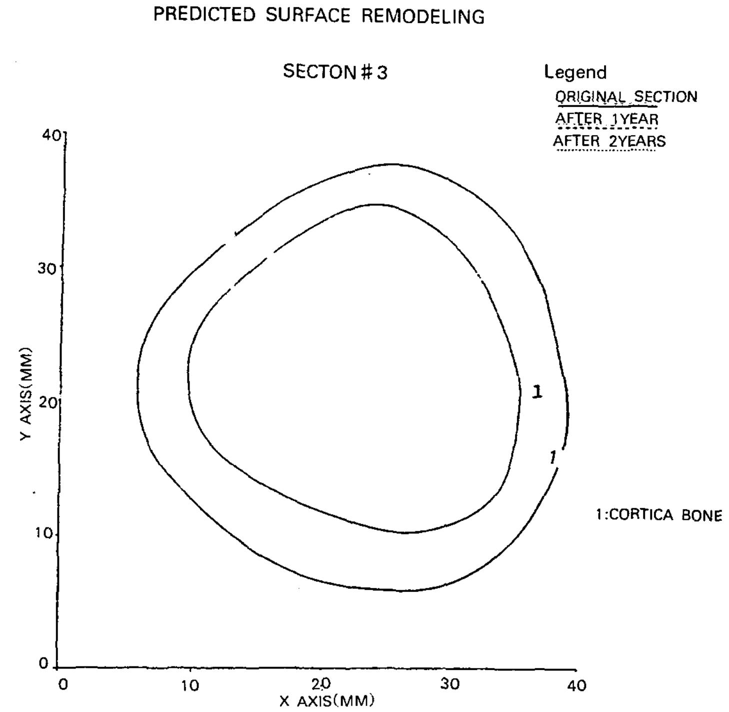


Figure 4 Predicted surface remodeling of the implanted human femur at section # 3

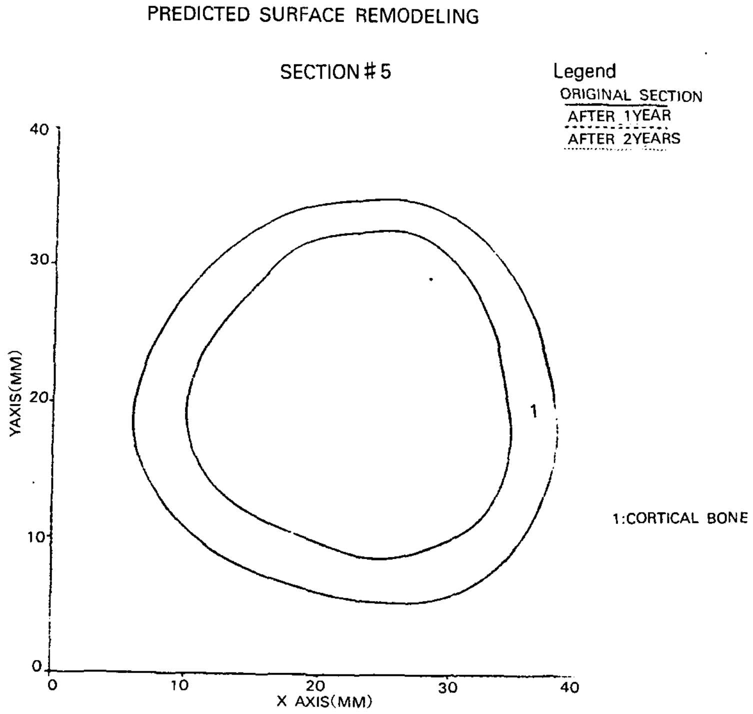


Figure 5 Predicted surface remodeling of the implanted human femur at section # 5

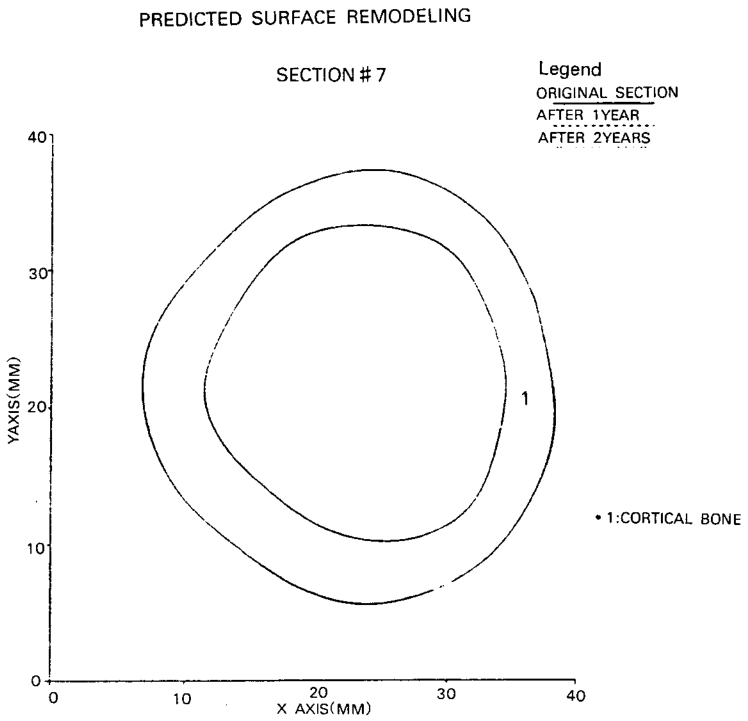


Figure 6 Predicted surface remodeling of the implanted human femur at section # 7

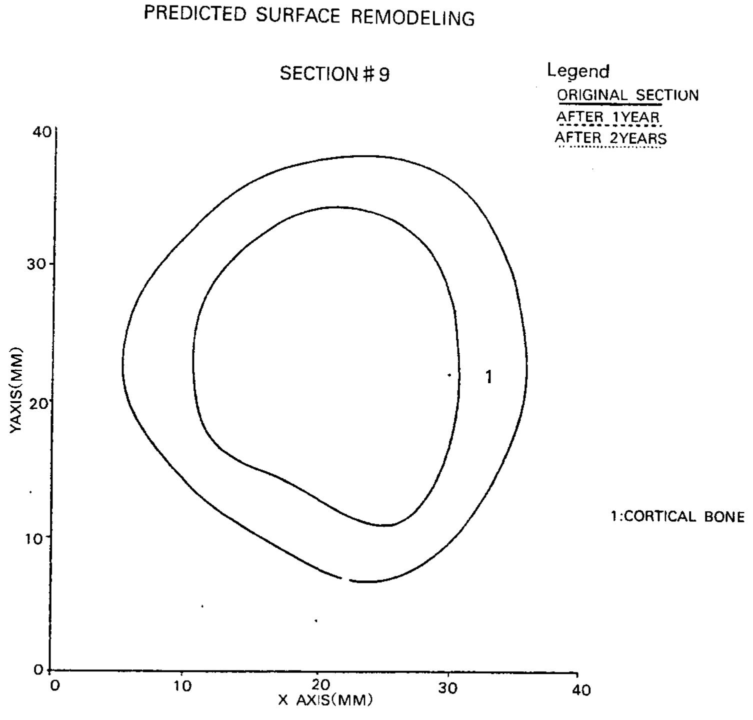


Figure 7 Predicted surface remodeling of the implanted human femur at section # 9

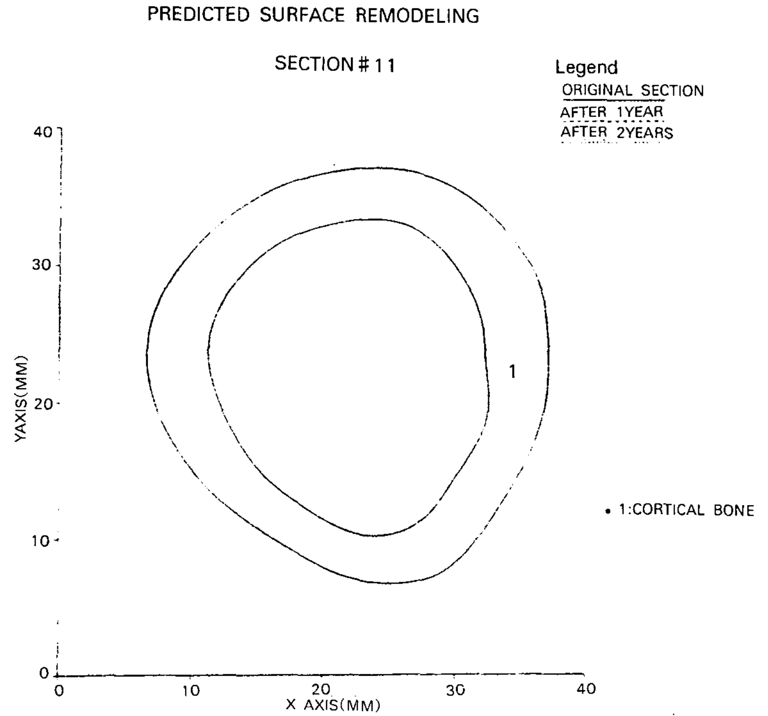


Figure 8 Predicted surface remodeling of the implanted human femur at section # 11

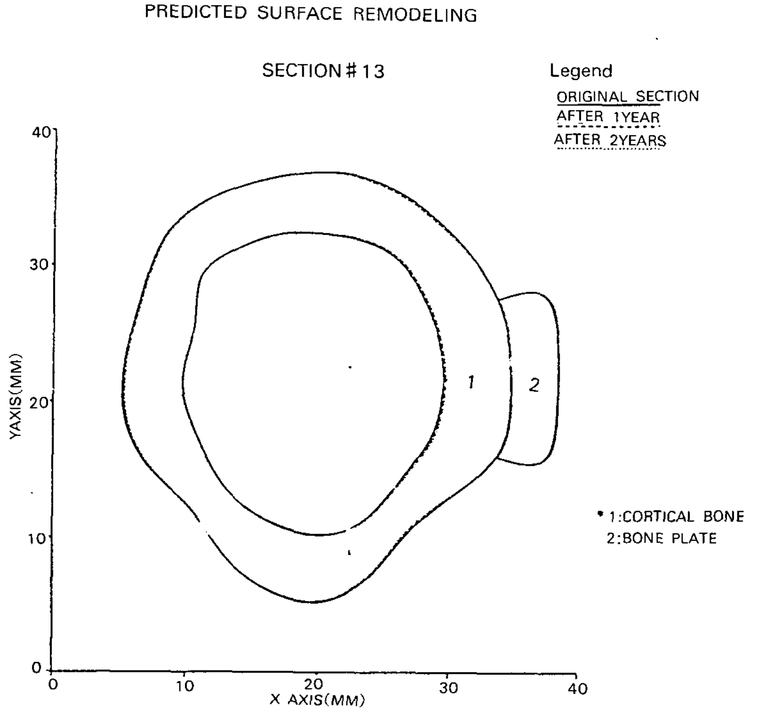


Figure 9 Predicted surface remodeling of the implanted human femur at section # 13

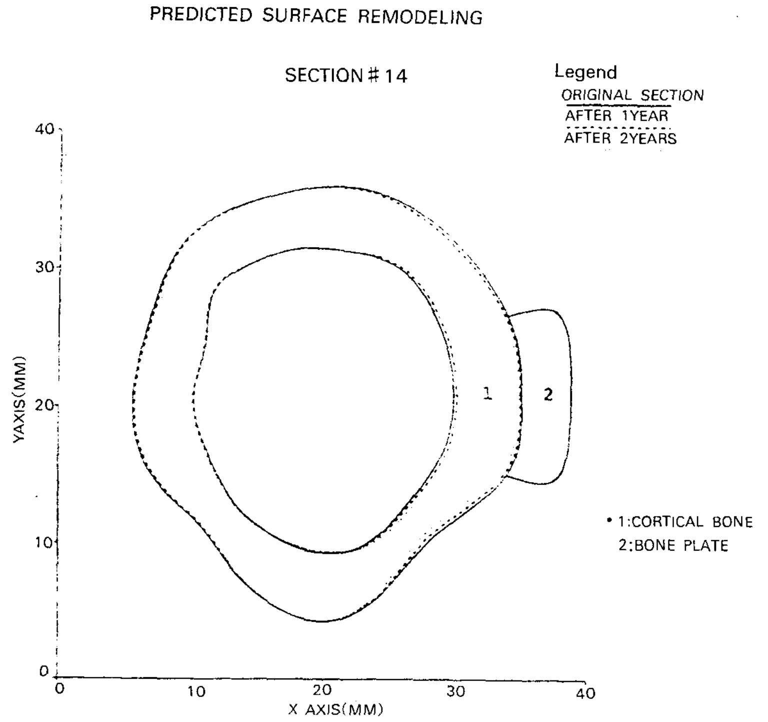


Figure 10 Predicted surface remodeling of the implanted human femur at section #14

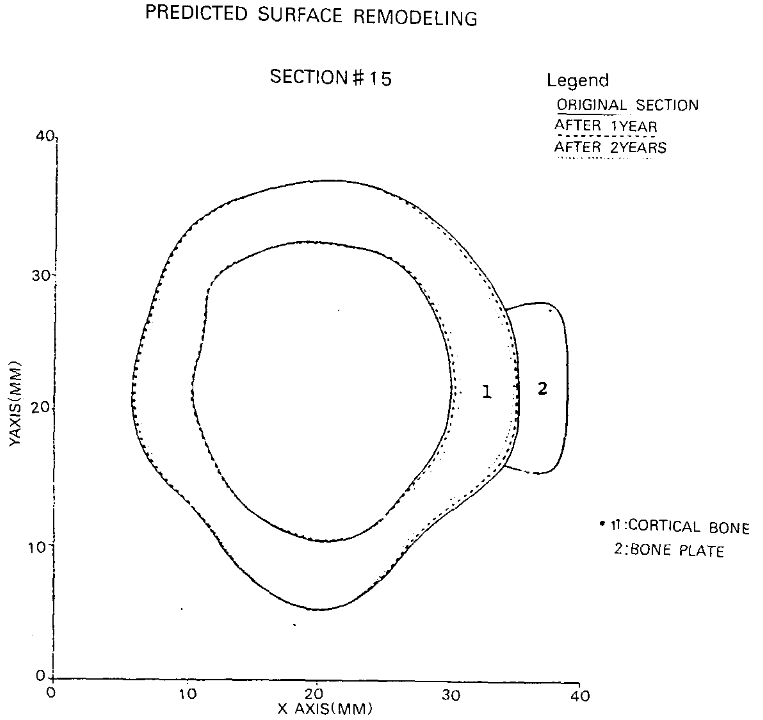


Figure 11 Predicted surface remodeling of the implanted human femur at section #15

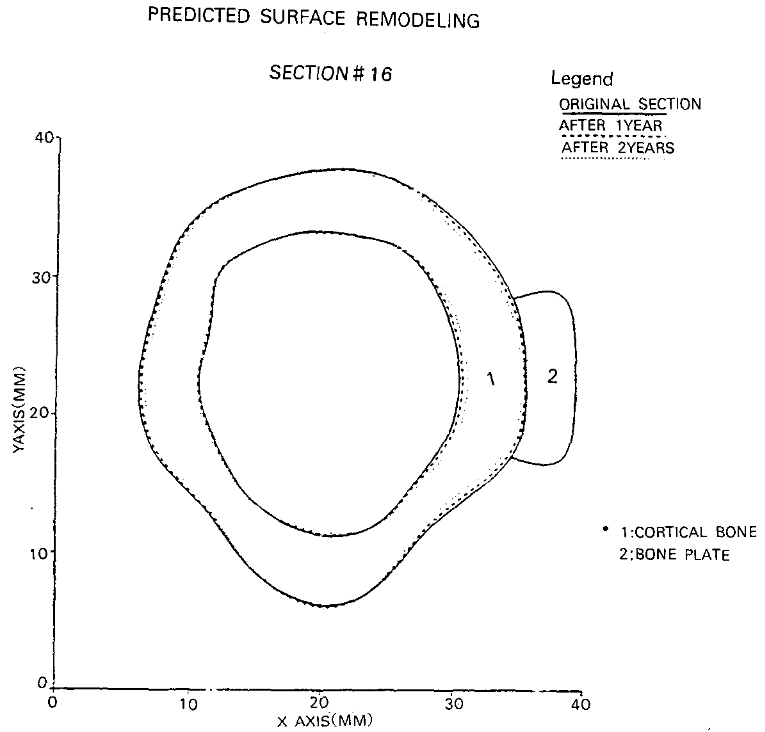


Figure 12 Predicted surface remodeling of the implanted human femur at section # 16

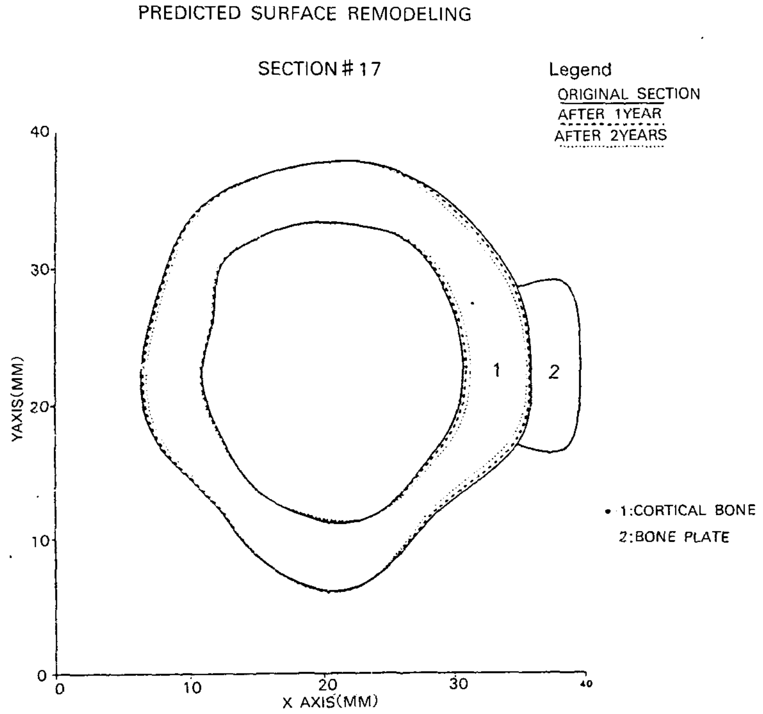


Figure 13 Predicted surface remodeling of the implanted human femur at section # 17

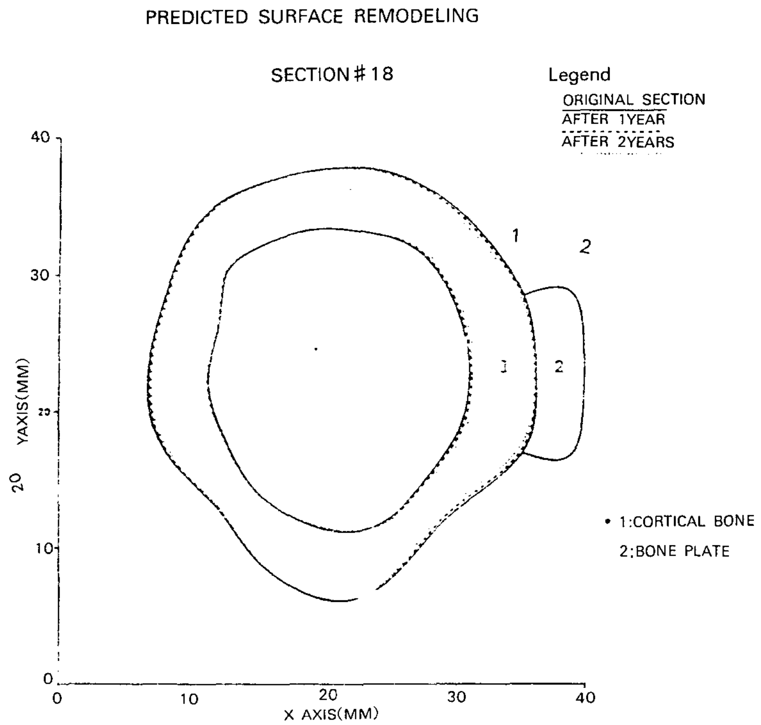


Figure 14 Predicted surface remodeling of the implanted human femur at section # 18

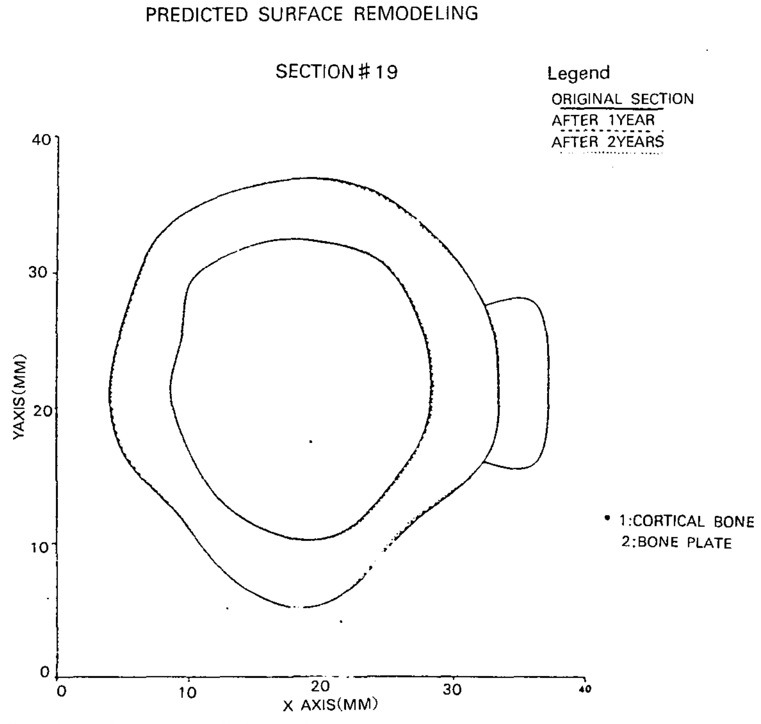


Figure 15 Predicted surface remodeling of the implanted human femur at section # 19

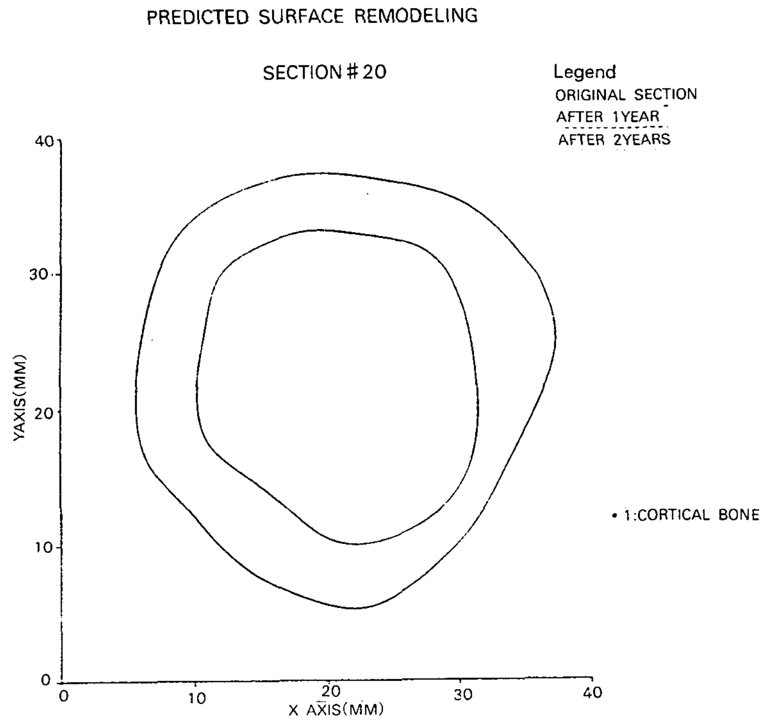


Figure 16 Predicted surface remodeling of the implanted human femur at section #20

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. (1976), Akeson et al. (1976), Moyen et al. (1978). However for the opposite site the third is somewhat different. Thus, it is inferred that the enlargement of the medullary canal is predominantly caused by 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 %13, %14, and %18, %19). 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 「15「2」.

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 results of the SDM is consistent with the experimental evidence, a human femur, implated 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 1 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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6. REFERENCES

(1) S.L-Y. Woo, W.H. Akeson, R.D. Coutts, L. Rutherfod, D. Doty, G.F. Jemmott, andl D. Amiel, : A comparison of cortical bone atrophy secondary to fixation with plates with large differences in bending stiffness : J.Bone Jt. Surg., 58-4, pp. 190~195, (1976)

(2) W.H. Akeson, S.L-Y. Woo, R.D. Coutts, J.V. Mattews, M. Gonsalves and D. Amiel, : Quantitative histological evaluation of early fracture healing of cortical bones immobilized by stainless steel and composite plates : Calcif. Tiss. Res., 19, pp. 27~37, (1975)

(3) D.R. Carter, R. Vasu, and W.H. Harris : The plated femur;Relationships between the changes bone stresses and bone loss : Acta Orthop, Scand., 52, pp. 241~248, (1981)

(4) S. Hidaka, and R. B. Gustilo, : Refracture of bones of the forearm after palte removal : J. Bone Jt. Surg., 66-A, pp. 1241~1243, (1984)

(5) H.K. Uhthoff, and F.L. Dubuc, : Bone structure changes in the dogunder rigid internal fixation : Clin. Orthop. & Relates Res., 81, pp. 165~170, (1971)(6) A. J. Tonino, C.L. Davidson, P.J. Klopper, and L.A. Linclau, : Protection from stress in bone and its effects : J. Bone Jt. Surg., 58-B, pp. 107~ 113, (1976)

(7) P. Hutzchenreuter, R. Mathys, H. Walk, and H. Brummer : Polyacetal plates with a metal core : in Current concepts of internal fixation of fracture, Uhtoff, H. K. (ed), Berlin, Springer Verlag., 149~155, (1980)

(8) L. Clases, C. Burri, L. Kinzl, E. Fitzer, and W. Hutter : Less rigid fixation with carbon fibre-reinforced materials;mechanical characteristics and behavior in-vivo : in Current concepts of internal fixations of fracture, Uhthoff, H. K.,(ed), Berlin, Springer Verlag, pp. 156~159, (1980)

(9) S. F. Corcoran, J. M. Koroluk, J. R. Parsons, H. Alexander, and A. B. Weiss : The development of a variable stiffness, absorbable composite bone plate : in Current concepts of internal fixation of fracture, Uhthoff, H. K., (ed), Berlin, Springer Verlag, pp. 136~145, (1980)

(10) M. Zimmerman, J.R. Parsons, and H. Alexander : The design and analysis of a laminated partially degradable composite bone plate for fracture fixation : J. Biomed. Mater. Res., 21, pp. 345~361, (1987)

(11) N. Tomota, and T. Kutsuna, : Experimental studies on the use of a cushioned plate for internal fixation : Int. Orthop., 11, pp.135~139, (1987)

(12) B.J-L. Moyen, P.J. Lahey, E.H. Weinberg, and W. H. Harris, : Effects on intact femora of dogs of the application and removal of metal plates : J. Bone Jt. surg, 60-A, pp. 940~947, (1978)

(13) R Huiskes, and D. Nunamaker, : Local stresses and bone adaptation around orthopaedic implants : Calcif. Tiss. Int., 36, pp. S110~S117, (1984)

(14) B.K.F. Kummer, : Biomechanics of bone, mechanical properties, functional structure, functional adaption;in Biomechanics : Its foundations and objectives, Fung, Y.C.(ed), Prentice Hall Inc. Englewood Cliff, N. J. pp. 237~271, (1972)

(15) H.S. Kim, : Numerical analysis of stress shielding of plated-human femur using 3-dimensional finite element method : KSME J., Vol. 5, No.1, pp. 3~9, (1991)

(16) R.B. Ashman, S.C. Cowin, W.C. Van Buskirik, and J.C. Rice : Continuous wave technique for the measurement of the elastic properties of corticall bone : J. Biomech., 5, pp. 349~361, (1984)

(17) . D. Mcleish, and J. Charnley, : Abduction forces in the one-legged stance : J. Biomech., 3, pp. 191~209, (1970)

응력해석에 의한 골절판이 부착된 인체 대퇴골의 골재형성 예측에 관한 연구

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초 록

뼈는 주변 여건에 따라 뼈의 재질 및 형상이 변하는 일종의 動的 구조물로서, 보철물이 부착되면 뼈의 응력상태가 다라져 새로이 骨재형성을 하게 된다. 특히, 골절판 부착시 뼈의 접촉은 촉진되나, 그 부위의 응력 변화에 의하여 골절판과 부착된 부분의 뼈는 오히려 약화되는 골다공증 현상을 야기하기도 한다.

본 연구에서는 뼈의 응력변화와 骨재형성의 관계를 3차원 유한 요소법을 이용하여 관련시키고자 한다. 이는, 새로이 설계된 골절판 또는 어떤 보철물이, 비록 그 자체의 생체 적합성 및 충분한 강도를 갖게 되더라도 골재형성에 미치는 영향을 판단할 근거가 요구된다고 사료되기 때문이다. 그래서, 현 사용되는 골절판을 인체 대퇴골에 부착된 3차원 유한 요소 모델을 제작하여, 응력 차이법에 의한 骨재형성의 경향을 조사하고, 그 경향을 기존 동물 실험결과와 비교 검토하여, 본 연구의 타당성을 평가하여 보철설계의 역학적 기초를 확립하고자 한다.