Correlation between Mechanical Stress in Finite Element Studies and Bone Mineral Density in the Femur after Total Hip Arthroplasty

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Introduction
Periprosthetic bone loss is one of the major concerns in total hip arthroplasty (THA). Severe periprosthetic bone loss may contribute to aseptic loosening of the prosthesis or to the risk of periprosthetic fracture. Several studies have reported that bone mineral density (BMD) decreases after THA, especially in the proximal femur. Most periprosthetic bone loss occurs during the first postoperative year, and BMD is maintained thereafter. This phenomenon is explained as an adaptive remodeling response of bone tissue to a significant alteration in its stress environment. Therefore, mechanical stress may relate with the patterns of BMD changes. The purpose of this study was to evaluate the pattern of load transfer after stem implantation, and to compare the stress of finite element (FE) studies to BMD in the proximal femur after THA.

Materials and Methods
This prospective study was approved by our Institutional Review Board. Twenty patients (13 women and 7 men) who underwent primary cementless THA with implantation of the same fit and fill type prosthesis formed the basis of this study. Informed consent was obtained from all patients. The mean age of the patients at THA was 63 years (range: 44–82). BMD was measured with dual-energy X-ray absorptiometry (DEXA) at 1 week and 12 months after THA. Regions of interest (ROIs) were defined according to Gruen’s system (ROIs 1–7). Computed-tomography (CT) images of the femurs of all patients were taken pre- and post-operatively with a slice thickness of 2 mm. FE models of the femur and stem were obtained from pre- and post-operative CT data by Mechanical Finder (Research Center of Computational Mechanics Inc., Tokyo, Japan), software that creates FE models showing individual bone shape and density distribution. Three-dimensional FE models with 1 to 4 mm tetrahedral elements for the trabecular and inner cortical bone and three nodal-point shell elements with a thickness of 0.3 mm for the outer surface of the cortical bone were constructed for each patient. The FE models of the femur consisted of approximately 600,000 elements, in addition to 200,000 elements for the stem. The mechanical properties of the bone were determined from CT density values, using the equations proposed by Keyak et al. The material properties of the stem were assumed to be an isotropic titanium alloy with an elastic modulus of 110.0 GPa and Poisson’s ratio of 0.30.

One loading condition was simulated. The shaft was fully restrained and force was applied to the femoral head and the greater trochanter. (Fig. 1) Von Mises stress and strain energy density (SED) were analyzed in ROIs 1 to 7 and compared to the DEXA data. The correlation between BMD and other values was analyzed by the Pearson’s product moment correlation coefficient.

Results
BMD was maintained at 1 year after THA in ROIs 3, 4, 5, and 6, whereas BMD decreased in ROIs 1, 2, and 7 by 19%, 14%, and 28%, respectively. This means that BMD had decreased, especially in the proximal femur, at 1 year after THA. FE studies revealed that the stress and the strain energy density were maintained in ROIs 3, 4, and 5 after THA, whereas both decreased in ROIs 1, 2, 6, and 7 (Figure 2 and Table 1). There was a significant correlation between BMD and von Mises stress (P<0.01) and between BMD and SED (P<0.05) (Figure 3, 4).

Discussion
Several previous studies have described the application of finite element studies to investigate strain adaptive bone remodeling patterns around implants, but most of these models are not subject-specific, and the mechanical properties of the bone were homogeneous. In our study, all patients underwent CT scans pre- and post-operatively, and we could investigate bone heterogeneity by using Mechanical Finder software, so we could construct subject-specific FE models.

Strain adaptive bone remodeling theory was used to simulate the change in BMD after THA. Huiskes et al proposed that changes in SED are assumed to be the remodeling stimulus. The present study demonstrated that low stress and strain energy density contribute to a decrease in BMD in the femur at 1 year after THA.

This study has several limitations. All analyses were performed using only one static loading condition, and activity levels of the patients were not taken into account. Further studies involving various loading conditions are necessary to reproduce postoperative conditions.

References

Table 1. Results of SED, von Mises stress and BMD (postoperative values compared to preoperative values)