Bone Remodeling Characteristics of a Short-Stemmed Total Hip Replacement

Hsiang-Ho Chen1, Bernard F. Morrey2, Kai-Nan An2, Zong-Ping Luo3

1Physiology, Taipei Medical University, Taipei, Taiwan; 2Orthopaedics, Mayo Clinic, Rochester, MN; 3Florida Orthopaedic Institute, Temple Terrace, FL

zluo@floridaortho.com

Introduction: Intense efforts continue to develop a "conservative" short-stemmed implant to replace the femoral side of a total hip arthroplasty (THA) that favors physiologic bone remodeling [1]. The assumption of this design is that the implant should not cause stress shielding or stress overload [2]. Ideally the presence of the implant will stimulate favorable or increased bone formation about the device. However, a biomechanical validation of this key concept requires direct acquisition of bone remodeling data from THA recipients and systematic analysis of the clinical findings. We report here a combined study of long-term clinical outcomes after the short-stemmed THA and further theoretical analysis of the bone remodeling characteristics.

Materials and Methods: The study included 29 patients undergoing the total hip replacement using the Mayo Conservative Hip (Zimmer International, Warsaw, IN). All were of an age of less than 75 years with adequate quality of bone as determined by rigid fixation of the rasp, and a body weight of less than 90 kg. All the patients had the unilateral replacement and the contralateral was used as the control.

The bone mineral density (BMD) of the periprosthetic femur and contralateral femur was evaluated in the anterior-posterior plane by the dual-energy X-ray absorptiometry (DEXA) (DPXL, Lunar Co., Madison, WI). The femur was divided into seven zones according to Gruen’s classification [3]. The mean and standard deviation were calculated for absolute change and percentage change in bone mineral density. Paired t-test was used to analyze the difference between the total hip arthroplasty hip and the control with significance at p<0.05.

The bone remodeling after total hip arthroplasty was simulated by a theoretical model based on the assumption that the bone is a biological optimized material which tends to maximize its resistance with minimum of structural consumption [2]. The calculation was carried out in a numerical iteration. First, the iteration started from the normal bone density distribution. A two-dimensional (2D) finite element model of the femur with the prosthesis (ALGOR, Inc., Pittsburgh, PA) was used to calculate the stress distribution. From the remodeling scheme, the updated bone apparent density and elastic modulus distribution was calculated from a remodeling signal. In the next iteration, the finite element was used to calculate the stress distribution, and new bone apparent density and elastic modulus distribution was updated. The iteration continued until the bone apparent density converged.

The 3D effects on the remodeling were taken into account with a side-plate connecting the peristeal sides of the medial and lateral cortices. To simulate the condition during one-legged stance, the loadings were applied as distributed forces to the joint surface (2317 N) and the trochanter (703 N). The femur was fixed at the distal end of the middle shaft. The relationship between bone apparent density ρ and Young’s modulus E was taken as E=3790 ρ + 300, the minimal bone apparent density was 0.01 g/cm3, representing complete bone resorption. The maximal bone apparent density was 1.74 g/cm3 when the bone was saturated and became cortical bone. The Young’s modulus for the implant was assumed to be 110 GPa; The Poisson’s ratio was taken as 0.3.

Results: DEXA demonstrated that the BMD range among all the individuals was from 0.29 to 3.28 g/cm2 (mean: 1.48 ±0.28 g/cm2) (Figures 1). The lowest density was found in zone 1 (0.78±0.17 g/cm2), and the highest was in zone 3 (2.18±0.33 g/cm2). Compared to the contralateral side, changes in bone mineral density were found in most zones. Significant decrease was found proximally in zone 1 (14.4%, p<0.0001), zone 6 (14.4%, p<0.0001) and zone 7 (17.9%, p=0.01). No difference was in zones 4 and 5. Increase of bone mineral density was shown in zone 2 (9.2%, p<0.01) and zone 3 (20.9%, p<0.0001), both of which are on the lateral side.

The von Mises stress distribution from theoretical model showed that the stress more concentrated around distal lateral canal and medial cortex. The high stress is transferred into the bone at the locations directly contacting with the cortex, one at the lateral cortex, and the other at the medial cortex more proximally below the calcar.

In response to the stress environment alterations, the remodeling process tended to have the highest bone apparent density in zone 3 (1.10 g/cm3) and the lowest in zone 1 (0.37 g/cm3). The normalized DEXA (against that in zone 4) showed a good agreement with the maximal deviation was in zone 7 (0.23) and the minimum was in zone 1 (0.003).

Discussion: To our knowledge, this was the first study to combine the clinical bone density DEXA with quantitative theoretical analysis to evaluate the long-term bone remodeling characteristics of short-stemmed femoral component. The clinical finding was consistent with the theoretical prediction, suggesting that the remodeling was largely regulated by mechanical environment alterations in stress distribution after arthroplasty. The alterations were defined by design characters of the short-stemmed implant: In the tight implant-cortex contact areas, high stress occurred with increased bone density (zones 2 and 3). In other areas which stress transfer was minimal, significant bone resorption was found.

In comparison to the traditional long-stemmed femoral component, the short-stemmed implant has much less bone resorption. The average bone loss found in this study was 3.3%, while the typical bone loss in the long-stemmed implant was about 20% [2]. This finding supported the design feature of the short-stemmed THA: the short-stemmed femoral component could conserve proximal bone and to achieve more proximal load transfer into the femur to reduce proximal stress shielding [1].


Acknowledgements: We acknowledge with gratitude the efforts of Bob Adams for patient scheduling and assessment.

Figure 1. DEXA images of both femurs which were divided into seven Gruen zones.