Comparison of Stress Shielding among Different Cement Fixation Modes of Femoral Stem in Total Hip Arthroplasty – A Three-Dimensional Finite Element Analysis

Weng-Pin Chen[1] Ching-Lung Tai[1, 2] Mel S. Lee[2] Po-Chen Lee[2]

Chun-Ping Liu[1] Chun-Hsiung Shih[2, 3,*]

[1]*Department of Biomedical Engineering, Chung Yuan Christian University, Chung-Li, Taiwan, 320, ROC*
[2]*Department of Orthopedic Surgery, Chang Gung Memorial Hospital, Tao-Yuan, Taiwan, 333, ROC*
[3]*Department of Orthopedic Surgery, Chung Shan Hospital, Taipei, Taiwan, 106, ROC*

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Abstract

Local bone loss after cementless and cemented implantation of prostheses remains an unsolved problem during the long-term application of total hip replacement. Stress shielding is considered to be one of several important factors that result in local bone loss after prosthesis implantation. This study was designed to investigate the roles of bone cement in different fixation configurations on initial stress shielding using a three-dimensional finite element analysis. Synthetic femora were used to create four finite element models including intact, and femora after implantation of C-fit stem with three different configurations of cement fixation: cementless, proximally-cemented and fully-cemented fixations. Under a 1,000-N vertical loading, the proximal strain distributions of the four models were analyzed and compared. The results revealed that, regardless of cement fixation configurations, stress shielding was found at the proximal femur following the insertion of stem. Less stress shielding was found for femur with fully-cemented fixation, whereas the most obvious stress shielding was found in the femur with cementless fixation. The introduction of bone cement was considered to produce more uniform transmission of external force, which led to the reduction of stress shielding.

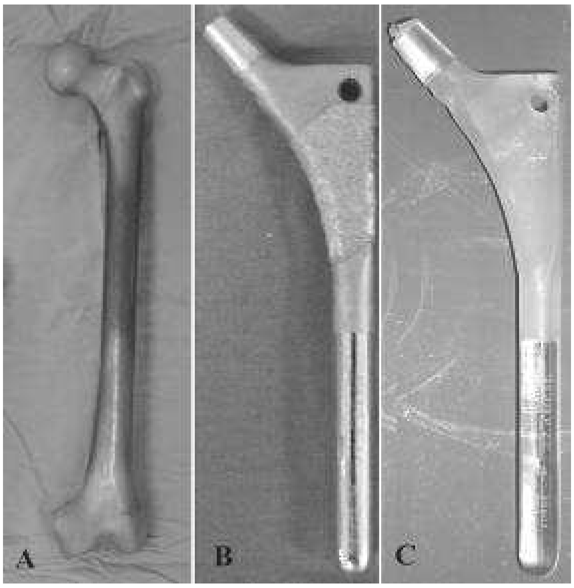
***Keywords*:** Finite element analysis, Stress shielding, Cemented fixation, Total hip arthroplasty

Introduction

Periprosthetic bone loss is one of the most common complications after total hip arthroplasty (THA). Loss of periprosthetic bone mineral can compromise the outcome of arthroplasty and may lead to the loosening and migration of prosthesis, periprosthetic fracture, and to problems in revision arthroplasty. The mechanism of bone loss adjacent to the implant is multifactorial [1]. Stress shielding and osteolysis are believed to be the most important causes of periprosthetic bone loss [2-4]. Stress shielding phenomenon means the tendency of bone to atrophy under mechanical unloading based on the principle known as Wolff's Law. *In vitro* studies showed that the calcar region is exposed to greater compressive stresses than the distal regions of femur. However, this stress pattern is reversed after the insertion of femoral prosthesis [5-8]. Adaptive remodeling occurs after the insertion of cemented and uncemented femoral stems, and it is more pronounced around large diameter, high stiffness stems [9]. Although bone loss caused by stress shielding is seldom the only reason for the failure of total hip arthroplasty, there is concern that periprosthetic bone loss may reduce the stability of stems [10-12].

In clinical practice, because of the individual anatomic difference in proximal femoral canal, bone cement fixation is usually recommended when the stem is not matched with the proximal femoral canal. This problem occurs more frequently during the revision surgery after aseptic loosening of lateral hip arthroplasty. On condition that the proximal femur canal exists a large range of the cavity during the revision surgery, the application of bone cement to fill the cavity of proximal femur is one of the optimal methods to contact the prosthetic component with the proximal portion of the femoral canal. However, in a thorough literature review, there is no report concerning about the biomechanical performance on condition that the cement fixation performed only in the proximal femur.

*Corresponding author: Chun-Hsiung Shih M.D.
Tel: +886-3-3281200 ext. 8145; Fax: +886-3-3278113
E-mail: ortholab@adm.cgmh.org.tw



(a) (b) (c)

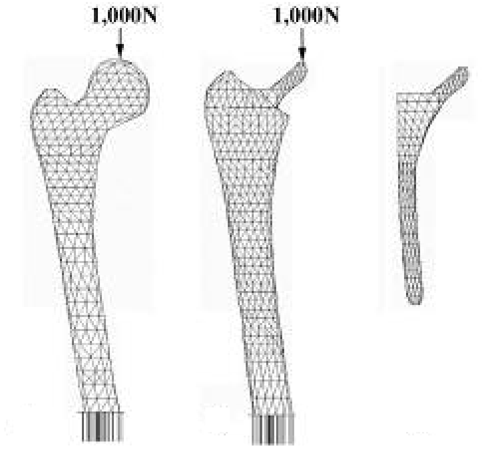
Figure 1. Figure showing (a) the synthetic saw bone, (b) Co-Cr C-fit stem and (c) methacrylate-made stem with identical geometry as Co-Cr C-fit stem.

From the viewpoint of biomechanics, the difference in the stability whether or not using bone cement, and the bone loss due to the stress shielding effect, are the two major factors causing stem loosening after THA.

The purpose of this study is thus designed to explore the correlation of the above-mentioned factors on the long-term stability using a three-dimensional finite element analysis (FEA), in hoping to overcome the problem of stem loosening and to extend the life expectancy of THA. The results acquired from these methods were analyzed and compared. It is hoped that there will be better understandings of the influence of bone cement fixation configurations on the bone loss, and aid in future clinical applications.

Materials and Methods

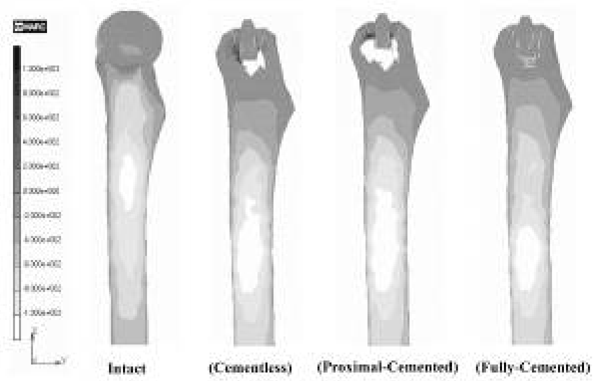
The femora used for the FEA were commercially available synthetic products (Pacific Research Laboratory Inc., Vashon Island, WA, USA) to eliminate the variations in between subjects. They were manufactured from a composite glass fiber/epoxy resin material to form cortices with internal cavity filled with polyurethane foam (Fig. 1a). The stem used was C-fit straight-type stem made of cobalt-chrome (Co-Cr) alloy (Corin, Cirencester, Glos., England) (Fig. 1b). Since the scattering effect of Co-Cr alloy may cause an undistinguishable contour in the CT image, methacrylate-made stems with identical geometry as the Co-Cr C-Fit stem was made by a molding procedure for the purpose of CT scanning (Fig. 1c). Four 3-D finite element models were created using computed tomography (CT) images based on four different configurations of stem fixation: the intact, cementless, proximally cemented and fully cemented. In the beginning, the CT scan images of the intact femur and the femur with cementless stem fixation were obtained at 2 mm intervals in the transverse planes from the femoral head down to the mid femoral shaft using a GE Hispeed scanner (General Electric, Milwaukee, WI, USA). The cross-sectional image files of the femur and the implant were transferred to a custom-written automatic contouring program for the detection of the contours for the cortical bone, cancellous bone, and prosthesis. Due to the sharp difference in density between the composite cortex, polyurethane medullary canal, and methacryate (C-Fit stem), accurate definition of the boundaries was facilitated. The two sets of parallel contours were then input into the NUAGES program (INRIA, Sophia, Antipolis, France) for the reconstruction of 3-D solid models. In the NUAGES program, the cementless femur was modified to create the proximally-cemented femur by assuming the stem to be surrounded by bone cement with 1 mm thickness superior to the lesser trochanter, whereas the fully-cemented femur was created by assuming the stem to be entirely surrounded by bone cement with 1 mm thickness. In both cases, the assumed cements were replaced from the femur materials. The four solid models were then transferred to a finite element pre- and post-processing program (Mentat 2000, MSC Software Corp., Los Angeles, CA, USA) for the generation of 3-D meshes. The tetrahedral elements were automatically generated in the Mentat program.



(a) (b) (c)

Figure 2. Figure showing the 3-D finite element models created from computed tomography (CT) images. (a) intact, (b) femur with C-fit stem insertion and (c) C-fit stem.

All materials were assumed to be linear, elastic, homogeneous and isotropic [13-15]. According to the specifications provided by the manufacturer, the Poisson's ratios for all materials were set to be 0.3 and the modulus of elasticity used for the cortical bone (composite glass fiber/epoxy resin), cancellous bone (polyurethane foam) C-Fit (Co-Cr alloy) prosthesis and PMMA bone cement were set to be 14.2 GPa, 50 MPa, 210 GPa and 2.8 GPa, respectively. Analysis was performed for the loading condition with 1,000 Newton vertical force applied on the femoral head. The distal ends of the femoral models were constrained as boundary condition. Fig. 2 illustrates the three finite element meshes of the intact femur, the stem- implanted femur, and the C-Fit stem with the loading condition indicated. The bone/stem,



(a) (b) (c) (d)

Figure 3. Medial view of axial normal strains for (a) intact, (b) cementless, (c) proximally-cemented and (d) fully-cemented femora. (Unit: microstrains)

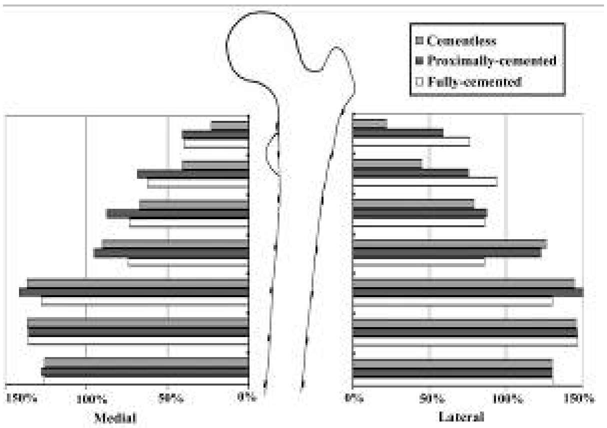


Figure 4. Axial normal strains of the implanted femora presented as percentages of the intact values.

bone/cement and cement/stem interfaces in the implanted models were assumed fully bonded without taking into account the micromotions. The finite element analysis for each of the three models was performed using the MARC 2000 finite element software (MSC Software Corp., Los Angeles, CA, USA) on an HP SPP/2000 supercomputer at the National Center for High-Performance Computing (NCHC, Hsinchu, Taiwan, R.O.C.). The analysis results were retrieved back to a local workstation for post-processing.

Results

The axial normal strains for the intact, cementless, proximally-cemented and fully-cemented femora on the medial aspects are shown in Fig. 3. Higher compressive strains were found on the proximal intact femur (ranged from the middle to the proximal neck regions) as compared to those of the cementless, proximally- or fully- cemented femora. Following the insertion of stem, the femora experienced an obvious reduction of axial normal strains in the proximal region, regardless of the cement fixation configurations. Fig. 4 illustrates the axial normal strains on the femoral surface of the proximal femora for the implanted femora presented as percentages of the values of intact femur. The results indicated that, regardless of the cement fixation configuration, the stress shielding in medial proximal femur is more significant as compared to those of lateral proximal femur. Femur with cementless fixation experienced the most reduction of normal strains on the proximal region as compared to those of the proximal- or fully-cemented femur. However, distal axial normal strains increased following the stem insertion regardless of the cement fixation configurations.

Discussion

Since the introduction of Charnley hip prosthesis in the early 1960's, total hip arthroplasty has proven to be a successful surgical procedure due to the improvements of prosthetic design, biomaterials and surgical technique [16,17]. However, there is still a great concern of bone loss associated with stress shielding and osteolysis [2-4]. This study was designed to use a three-dimensional finite element analysis to evaluate the role of different bone cement fixation configurations on the initial stress shielding.

The finite element analysis (FEA) has become a useful tool in analyzing the stresses in structures of complex shapes, loading and material behavior. Numerous applications in orthopedics analyzed by using FEA have been presented and proven to be a successful tool in predicting the mechanical characteristics of skeletal parts in interesting circumstances [18,19]. In the present study, higher compressive strains were found on the proximal intact femur (ranged from the middle to the proximal neck regions) as compared to those of the cementless, proximally- or fully- cemented femora. Following the insertion of stem, regardless of which cement fixation configuration, axial normal strains presented as percentage of the intact value indicated that the implanted femur experienced a significant reduction in axial normal strains at both medial and lateral sides of the proximal region (Fig. 4). The most significant reduction in strain was found in the femur with cementless fixation, this was concerned to lead to bone loss in the proximal femur for long-term application. A less strain reduction was found, however, following the introduction of bone cement. The results implied that the introduction of bone cement might lead to a more uniform stress distribution on the proximal femur in a long term. One important finding worth to be noted was that, following the insertion of stem, an increase in the axial normal strains appeared at the distal femur starting from the end of stem. The origin of this phenomenon was considered due to the compaction of bone resulted from the distal end of stem. Based on the Wolff's law, the increase of axial normal strains at the distal femur might increase bone density in long-term application.

The convergence of FEM model plays an important role on the reliability of the final results, whereas the method used in this study to validate the convergence of the model is to calculate the total strain energy of the structure. Three models of different numbers of element and node were created to perform the convergence test, and the results of the total strain energy for the three models were all within a 5% difference. In a global sense, the convergence test demonstrated the validity of the models established.

In summary, this study achieved the following findings:

(A) Regardless of fixation configuration, the stress shielding in medial proximal femur is more significant as compared to those of lateral proximal femur.

(B) Regardless of fixation configuration, stress shielding occurred following the implantation of stems. However, the stress shielding in femora with cementless fixation is more significant as compared to those with cemented fixation (either proximal- or full-cemented).

(C) Application of bone cement tends to decrease stress shielding and normalize the strain distribution of femoral surface.

(D) Following the insertion of stem, an increase in the axial normal strains appears at the distal femur starting from the end of stem.

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不同骨水泥固定方式對於全人工髖關節置換術後應力遮蔽之比較-有限元素分析

陳文斌[1] 戴金龍[1,2] 李炫昇[2] 李柏成[2] 劉俊平[1] 施俊雄[2,3,*]

[1]中原大學醫學工程研究所
[2]林口長庚醫院骨科
[3]台北中山醫院骨科

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摘　要

以骨水泥或無骨水泥方式施行人工髖關節置換手術後，股骨近端皮質骨發生區域性骨質流失現象始終是骨科界無法解決的問題。應力遮蔽被公認爲是造成骨質流失現象的主因之一。本研究以有限元素分析方法，針對無骨水泥、股骨柄上端包覆及股骨柄外圍全部包覆骨水泥等三種固定情況下，施行人工髖關節置換手術後三者間應力遮蔽及術後骨質流失的差異性。研究的方法，是利用人造股骨及電腦斷層影像分別建立完整股骨及以上述三種不同骨水泥固定方式施行人工髖關節置換手術後之股骨三維有限元素模型。在 1,000 牛頓的垂直壓力作用下，分別比較四種股骨之應變分佈差異性。分析結果顯示，無論以何種方式植入股骨柄，術後股骨近端均將產生應力遮蔽現象，其中以股骨柄上端包覆固定者所產生之應力遮蔽現象最爲輕微；無水骨泥固定者最爲顯著。我們研判，骨水泥的介入將使術後股骨應力分佈更爲均勻，有利於減輕應力遮蔽效應。

關鍵詞：有限元素分析、應力遮蔽、骨水泥、全人工髖關節置換

* 通訊作者：施俊雄
電話：+886-3-3281200 ext. 8145；傳真：+886-3-3278113
電子郵件信箱：ortholab@adm.cgmh.org.tw