Comparison of Stress Shielding between Straight and Curved Stems in Cementless Total Hip Arthroplasty – An *in vitro* experimental study

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Received 19 Nov 2004; Accepted 14 Dec 2004

Abstract

Adaptive bone remodelings in the proximal femur often occur following either cemented or uncemented total hip arthroplasty (THA). Stress shielding is one of the most significant determinants of this bone remodeling, and it results from changes in force distribution following prosthetic implantation. In order to evaluate the alteration of stress distribution after implantation of straight or curved femoral stem, this study was designed to compare the difference of stress shielding for straight and curved stems in cementless THA using in vitro experimental method. Uniaxial strain gauges and synthetic femora were used to perform the surface strain measurement of proximal femora. A total of eight synthetic femora were enrolled and assigned into C-Fit (Straight stem) and PCA (Curved stem) groups (four in each). Under 1,000-N axial loading, the surface strains of proximal femora were measured and compared between C-Fit and PCA implanted femora with press-fit fixation. The results revealed that the straight stem group got less stress shielding as compared to that of the curved stem group. We concluded that curved stem caused a more significant stress shielding as compared to those with straight stem.

***Keywords*:** Straight stem, Curved stem, Stress shielding, Strain measurement, Total hip arthroplasty

Introduction

Although the surgical reconstruction of the hip with total hip arthroplasty (THA) has proven to be a widely accepted treatment for severely clinical implication, however, it is limited by mechanical and biological failures [1-3]. Femoral component loosening is the most common mechanical failure and is of great concern. Stress shielding is a mechanical cause of bone loss and is characterized by adaptive remodeling changes in the proximal femoral cortex following stem implantation [4-6]. A major problem threatening the long-term integrity of total hip arthroplasty is the loss of proximal bone often found around stems in the long term [7-10]. It is generally accepted that "stress shielding" is one of the causes for this problem. After implantation of the prosthesis the surrounding bone is partially "shielded" from load carrying and starts to resorb [11-13]. Resorption, in the sense of reduced cortical thickness and increased porosity, is seen in most patients who have received noncemented THA. The proposed mechanism of stress shielding is based on Wolff's law of remodeling [1,2]. The redistribution of stress results in a decrease of the bone mineral density around the proximal femur, which may influence the longevity of the prosthesis [1,2, 11-13].

The purpose of this study is aimed to explore the correlation of the geometric factor of the stems on the long-term stability using *in vitro* experimental method, in hoping to overcome the problem of loosening to extend the life expectancy of THA.

Materials and Methods

The femora used were commercially available synthetic products (Pacific Research Laboratory Inc., Vashon Island, WA, USA), which were manufactured from a composite glass fiber/epoxy resin material to form cortices with internal cavity filled with polyurethane foam. The stems used in this investigation were anatomical-type PCA (Porous-coated

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(a) (b)

Figure 1. The curved PCA (left) and straight C-Fit (right) stems used for *in vitro* experiment. (a) A-P view; (b) Lateral view.

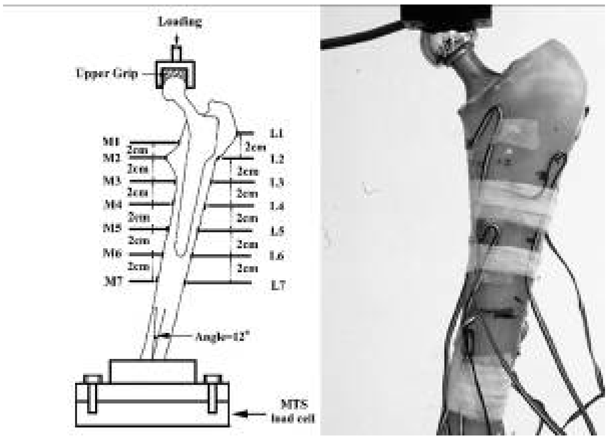


Figure 2. The experimental setup and locations of strain gauges performed in the *in vitro* experiment.

anatomic, Howmedica, Rutherford, NJ, USA) and straight-type C-Fit (Corin, Cirencester, Glos., England) stems (Fig. 1). They were all made of cobalt-chrome (Co-Cr) alloy. A total of eight synthetic femora were enrolled and assigned into C-Fit and PCA groups (four in each group). Thirty-centimeters long femur (measured vertically from the top of the femoral head) was harvested with a power saw for all eight intact femora. The distal femur was clamped to the load cell of the MTS testing machine (Bionix 858, MTS Corporation, Minneapolis, MN, USA) with a low-melting alloy. A matching acetabulum-like cupping was applied on the upper part of the fixture to transfer the load which was inclined 12° medial to the mechanical axis in the frontal plane. For the strain measurement of the proximal femur, the location of the horizontal height of the lesser trochanter was selected as a reference point on both medial and lateral aspects, respectively. A total of fourteen unidirectional strain gauges (KYOWA, KFC-5-120-C1-11, Kyowa Electronic Instrument, Tokyo, Japan) were mounted longitudinally onto the proximal femur with 2 cm intervals distal to the lesser trochanter on both the medial and lateral aspects (Fig. 2). The prepared femora were then subjected to axial loading with 1,000 Newtons using the MTS testing machine. 1,000 Newtons was found to be below the threshold value for permanent deformation based on the

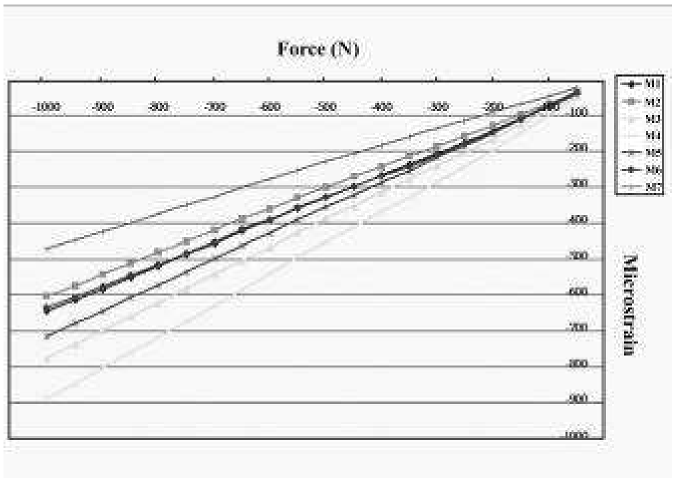


Figure 3. The typical diagram for the relation between applied force and strain in the medial aspect of the femur. The curves demonstrated that the strain magnitude increased linearly with increasing force for all measured sites.

linear relationship of load-strain curve in pretests. To determine the load-strain relationship up to 1,000 Newtons, the surface strain of the intact femora was measured first. The loading rate was set 20 Newtons per second and the strain at specific positions was collected simultaneously during the loading process by multi-channel signal amplifier (Measurements Group Inc., Raleigh, North Carolina, USA). Following strain measurement of the intact femora, all eight intact femora were randomly divided into C-Fit and PCA groups (four in each group). For each group, femoral heads were cut and replaced with C-Fit and PCA stems by cementless fixation. Strain measurements were repeated to determine the load-strain relationship after stem insertion. The testing conditions, which included the loading axis, strain gauge placement, and the testing procedures, were maintained identically for each test. Finally, the surface strains measured were compared between the C-Fit and traditional PCA implanted femora. The mean value of the surface strains at 1,000 Newtons on specific positions of the femora represented the results of the tests.

Results

The typical diagram for the relation between applied force and strain in the medial aspect of the femur was shown as Fig. 3. The curves demonstrated that the strain magnitude increased linearly with force increasing for all measured sites. Fig. 4 illustrated the surface strains of C-fit and PCA implanted femora presented as percentages of the measured intact values. Compressive strains were measured on the medial side, while the strains on the lateral side were tensile in each type of femur. The largest standard error for both the medial and lateral surface strains under 1,000 Newtons was less than 16% of the mean for all the gauges. Notably, the average surface strains of the proximal femora decreased obviously after implantation of the PCA prosthesis on both the medial and lateral sides (Fig. 4). Comparison of the strain data as measured in the C-fit and

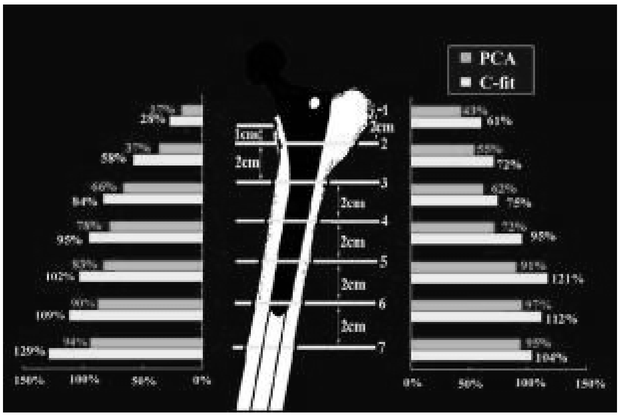
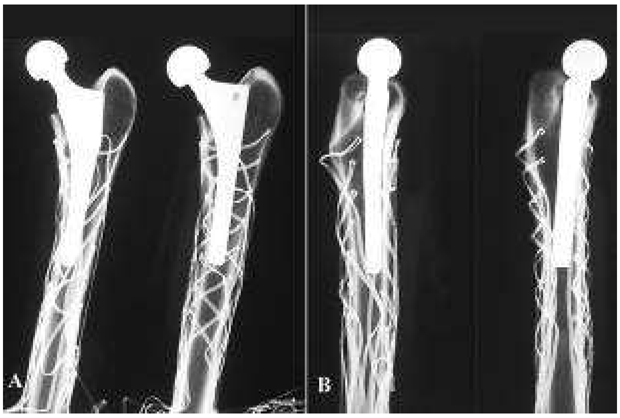


Figure 4. The surface strains of C-fit and PCA implanted femora presented as percentages of the measured intact values.



(a) (b)

Figure 5. The roentgenographic films of PCA (left) and C-Fit (right) implanted femora showing an adequate insertion of stems. (a) A-P view; (b) Lateral view.

PCA implanted femora showed obvious stress shielding in the PCA implanted femora as compared to that of C-fit implanted femora. Implantation of PCA prostheses significantly reduced the longitudinal strain in the proximal gauges. The most proximal medial (M1) and lateral (L1) femoral cortex of PCA implanted femora experienced approximately 17% and 43% of the strain of the intact femur, respectively. However, for the C-fit implanted femora, approximately 28% and 61% of the strain remained as compared to that of intact femur at the same positions. For both cases, the strain magnitudes tended to approach those of the intact femur as the positions progressed distally. In summary, the results of biomechanical test achieved two main findings: (1) The stress shielding in medial proximal femur is more significant as compared to lateral proximal femur in both C-fit and PCA stem replacements. (2) Stress shielding occurred following the prosthetic replacement, either C-fit or PCA stems. However, the stress shielding of PCA implanted femora is more significant as compared to that of C-fit implanted femora.

Discussion

Adaptive remodeling changes in the proximal femoral cortex occur following both cemented and uncemented total hip arthroplasty (THA). Stress shielding is one of the most significant determinants of this bone remodeling, and it results from changes in force distribution following prosthetic implantation [7-10]. The effects of stress shielding can be seen radiographically adjacent to the arthroplasty components. The proposed mechanisms of stress shielding are based on Wolff's law of remodeling. Many studies have demonstrated that there is a reduced stress in the proximal femur following prosthetic arthroplasy [11-15]. The proximal femur is bypassed as load is transferred through the prosthesis to the more distal cortical bone. This transfer of force to the prosthesis away from the proximal femur results in bone atrophy.

In the present study, commercial synthetic femora were used as a substitute for human femur. The material properties of human bone vary with age and species, creating variability among all subjects, and making it very difficult to achieve reliable and comparable experimental results. Recently, numerous investigations using the synthetic femur as a substitute for cadaveric specimens in *in vitro* tests have shown usefulness of these bones for predicting the mechanical characteristics in specified circumstances [13, 16-19]. The use of such femora was also proposed to simplify experimental set-up, limiting experimental error in the testing of different prosthesis designs. In the present study, the roentgenographic film of synthetic femora after implantation of PCA and C-Fit stems was shown as Fig. 5. The roentgenographic observation from the prosthetic femora indicated an adequate fixation of these stems, which ensures to the results of strain measurement to be more reliable. It needs to be pointed out that the strain gauges used in current study were all unidirectional, and mounted longitudinally onto the proximal femur. Consequently, the measured strain only represent the magnitude in direction corresponding to it mounted (femoral shaft). Although the gauges did not measure the principal strains in the current study, they did measure strains, which represented relative differences between the intact, C-fit and PCA cases. For both C-fit and PCA implanted femora, as shown in Fig. 4, a marked reduction of strain value occurred in the medial and lateral proximal femur when compared to the intact femur. However, the strain values are apparently lower in the most proximal PCA implanted femur as compared to those in the C-fit, revealing significant stress shielding following the implantation of PCA stem.

In any discussion of stress shielding and bone remodeling, it is helpful to consider several concepts related to stiffness or elasticity. Stems with equal stiffness (isoelasticity) as the femur might be considered an ideal design beneficial for avoiding stress shielding. The familiar term "isoelastic" means "equal in elasticity", and the definition derived from isoelastic is that an implant of the same stiffness as the femur is a desirable design objective. Imaginably, this seems reasonable. From an engineering standpoint, however, it may not be entirely realistic. Simple beam theory indicates that if two objects of equal stiffness are jointed, the composite object possesses twice the structural stiffness of the individual objects (assuming a uniform, well-bonded interface) and for any applied load will experience only half the strain or stress. Thus, in simplistic terms, an implant of equal stiffness to the femur could stress shield the bone by as much as 50%. This simple analogy is drawn for the purpose to mention that, in fact, besides the concerned "stiffness" factor, the analysis is complicated by fit, interface conditions, presence of bone ingrowth and other factors. In the actual application, the addition to the femur of any stem-type implant with any stiffness will cause some degree of stress shielding.

Two factors that may affect the results of the study need to be pointed out. First, the geometry and the material properties of a standard composite femur were used instead of those of femur from actual patient. The benefit of using a standard composite femur was to eliminate the variations in between subjects. On the other hand, the drawback was the overlook of the effects of the actual geometry and constitution of the bone. Second, the only loading condition considered was the vertical compression applied on the femoral head. Further investigation on the effects of other loading conditions such as cyclic loading might be necessary in the future.

Acknowledgement

This study was supported by a grant from National Science Council of the Republic of China (grant no. NSC 89-2320-B-182-052-M08).

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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無骨泥式對稱型及解剖型股骨柄人工髖關節置換術後應力遮蔽之比較研究-體外力學測試

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收件日期 2004 年 11 月 19 日；接受日期 2004 年 12 月 14 日

摘　　要

以骨泥或無骨泥方式施行人工髖關節置換手術後，股骨近端硬質骨均將發生骨質重塑改變。應力遮蔽效應是在諸多造成骨質重溯現象中最重要因素之一，其主要原因來自股骨柄於植入股骨後所產生的應力分佈重大改變。為深入了解目前臨床上常使用之對稱型及解剖型股骨柄於植入股骨後所產生骨質流失差異性，本研究乃設計以體外力學實驗，針對無骨泥固定情況下，以對稱型及解剖型股骨柄施行人工髖關節置換手術後，比較術後二者間應力遮蔽效應的差異性。實驗的方法，是利用單軸向應變規及人造股骨進行股骨近端硬質骨之表面應變量測。以八件人造股骨依股骨柄之外型區分為對稱型（C-Fit）及解剖型（PCA）兩組（每組四件），在 1,000 N 的壓力負荷下，分別比較上述二種不同幾何形狀之股骨柄在無骨泥植入情況下，二者間股骨近端硬質骨應變值的差異性。實驗結果顯示，在無骨泥植入情況下，植入解剖型股骨柄之股骨近端應力遮蔽效應較對稱型股骨柄顯著。本研究結果有效證實以無骨泥方式施行解剖型股骨柄置換手術後，將產生較明顯之應力遮蔽效應。

關鍵詞：對稱型股骨柄、解剖型股骨柄、應力遮蔽、應變量測、全人工髖關節置換術

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