Femoral Remodeling Around Charnley Total Hip Arthroplasty Is Unpredictable

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Abstract

Background There are two unusual remodeling patterns of the proximal femur around well-fixed Charnley total hip arthroplasties: cortical thinning leading to endosteal widening around the femoral component and hypertrophy of the distal femoral cortex. Previous studies have shown remodeling patterns are affected by stem design and occur early postoperatively. It is unclear if these changes are related to patient demographics or if they progress throughout the lifetime of the implant.

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Questions/purposes We determined if patient demographic variables influence remodeling patterns after cemented Charnley total hip arthroplasty and if the observed remodeling changes persist long-term.

Methods We retrospectively reviewed the radiographs of 106 well-fixed Charnley femoral components. Using a novel digital edge detection program, we determined the femoral remodeling pattern and time-related changes in femoral dimensions. The minimum followup was 20 years (mean, 25.3 years; range, 19.5–37 years).

Results We found no association between remodeling type and age at surgery, sex, preoperative diagnosis, body mass index, or postoperative activity level. There was also no association between initial implant alignment and remodeling type. Cortical thickening in the distal hypertrophy group was an early phenomenon occurring primarily within the first 2 years, whereas cortical thinning begins later and is a more progressive process.

Conclusions These data show remodeling after cemented Charnley total hip arthroplasty is not related to patient demographic variables; however, distal cortical hypertrophy can be predicted in the early postoperative period.

Level of Evidence Level IV, therapeutic study. See Guidelines for Authors for a complete description of levels of evidence.

Introduction

Normal remodeling of the proximal femur with age has previously been characterized by endosteal canal widening and decreasing cortical thickness [7, 18, 20]. THA changes the pattern of stress transmission in the proximal

femur. In 1968, Charnley et al. [4] observed two unusual patterns of remodeling of the proximal femur in response to the femoral component of well-fixed THAs: extreme cortical thinning leading to endosteal widening around the femoral component and hypertrophy of the distal femoral cortex. Previous studies have investigated the short- and mid-term remodeling of the proximal femur to cemented THA [1, 3–6, 8, 10, 14, 16, 17, 21]. Poss et al. [17] reported in 22 hips at a mean of 11.2 years followup that the proximal femur typically remodels with endosteal expansion and cortical thinning comparable to that seen with normal aging. Previous studies have shown that normal proximal femoral remodeling is characterized by cortical thinning and subperiosteal endosteal expansion, which is more pronounced in females [7, 18, 20]. Comadoll et al. [6] reported in 26 hips at a mean of 10.4-year followup decreased cortical thickness and widening of the medullary canal with no change in the total outer periosteal diameter. This increase in medullary canal diameter and associated thinning of the proximal femoral cortex are associated radiographically with the development of a radiolucent line. Kwong et al. [15] described that the radiolucency that appears radiographically between the bone-cement interface corresponds to an area of osteoporosis, cancellization, thinning of the endosteal cortex, and osteopenia of the trabecular bone but does not represent loosening of the prosthesis. Previous clinical studies on proximal femoral remodeling have focused on endosteal expansion and cortical thinning resulting from the perceived increased risk of aseptic loosening [6, 10, 17], whereas only one study has mentioned distal cortical hypertrophy since Charnley's original observation in 1968 [4, 14]. In this study, Kobayashi et al. [14] reviewed 326 Charnley femoral prostheses at a mean 13.3 years followup in an Asian population. They noted 29% of femoral components showed distal cortical thickening. They also noted 10% of hips showed excessive cortical thinning defined as cortical thinning proximally as well as distally. They noted that older age and a wider larger canal width were risk factors for excessive loss but did not investigate risk factors for hypertrophy. They also did not investigate whether component alignment influenced remodeling type. They also noted cortical thinning was progressive but did not investigate whether hypertrophy also occurred in a progressive manner.

We sought to determine (1) whether the type of pattern of remodeling would be influenced by patient demographic variables (sex, age, body mass index, activity level, preoperative diagnosis); (2) whether remodeling pattern is influenced by initial femoral component alignment; and (3) the time dependence of both of the unusual remodeling patterns of distal hypertrophy and excessive endosteal loss.

Patients and Methods

We retrospectively reviewed the radiographs of 102 patients who underwent 130 primary cemented Charnley THAs performed by a single surgeon (RCJ) from 1970 to 1978. During that same time, the surgeon treated 582 patients with 687 THAs. Of the total cohort, 417 patients had died or were lost to followup; 19 living patients were known to have been revised. We excluded 44 patients (44 hips) with inadequate serial radiographs. All 130 hips were previously evaluated by one of the authors (JJC) and were well fixed at minimum 20-year radiographic followup [13, 19]. Eighty-six hips were in female patients and 44 in male patients. The mean age at the time of surgery was 53.4 years (range, 22.9–70.4 years). The average body mass index was 26.1 kg/m² (range, 17.6–44.0 kg/m²). Preoperative diagnoses included developmental hip dysplasia in 56, primary osteoarthritis in 54, posttraumatic osteoarthritis in seven, slipped capital femoral epiphysis in five, postpolio in three, rheumatoid arthritis in two, and one each of avascular necrosis, Perthes disease, and conversion of arthrodesis. The minimum radiographic followup was 19.5 years (average, 25.3 years; range, 19.5–37 years).

All operations were performed through a transtrochanteric approach. All implants were stable at the time of last evaluation. The Charnley flat back femoral prosthesis was made of stainless steel and a polished surface finish was the only design used.

Patients were evaluated at 6 weeks, 3 months, 6 months, 1 year, and every 2 years thereafter. At each visit, patients were evaluated by a history, physical examination, a standardized questionnaire [12], and an AP pelvis radiograph. The average postoperative activity level assessed by the patient's highest self-reported activity on the standardized questionnaire [12] was 2.2 (range, 1–5).

We obtained AP pelvis radiographs in a standardized fashion in the supine position with a beam length of 91 cm. Only hips with serial radiographs of high quality were analyzed. We assessed rotational alignment of the proximal femur using the profile of the lesser trochanter and the femoral prosthesis on the AP pelvis radiograph [17]. Quantitative analysis of the cortical thickness and endosteal diameter was only performed for those radiographs with comparable rotational alignment. Femoral components were evaluated radiographically for loosening according to the criteria of Harris and McGann [9] and clinically by absence of thigh pain. Ninety-six hips were in neutral alignment, 31 hips were in valgus alignment, and three hips were in varus alignment [11].

We determined quantitative changes in the proximal femur for 106 of the 130 hips (82%) that had high-quality serial radiographs. The radiographic profile of the lesser trochanter and the femoral prosthesis were used to

determine whether the rotational alignments of the femora were comparable [17]. Fourteen were excluded because the entire femoral prosthesis was not visible on the minimum 20-year radiograph, five were excluded secondary to rotational differences, and five were excluded because one or more of the serial radiographs were underpenetrated. All radiographs were digitized. Measurements were made of medial cortical thickness, lateral cortical thickness, and total femoral diameter at four levels in the proximal femur: the inferior aspect of the lesser trochanter, the tip of the femoral component, a point midway between the inferior aspect of the lesser trochanter and the tip of the femoral component, and 25 mm distal to the tip of the femoral prosthesis. All measurements were corrected for magnification by scaling to the known diameter of the femoral head (22.25 mm). Measurements were made using a novel digital edge detection program on MATLAB® software (MathWorks, Natick, MA, USA), which identified the central longitudinal axis of the proximal femur and the four mentioned points perpendicular to the central longitudinal axis (Fig. 1). The program detects strong edges in images such as the outer cortical edge, thereby accounting for variations in gray scale as a result of different radiographic techniques. We performed serial measurements for each hip using the immediate postoperative, 2-year, 5-year, 10-year, 15-year, and 20-year radiographs. A total of 536 radiographs were analyzed. All measurements were made by a single experienced observer (MJT). Kappa coefficients

Fig. 1 This figure demonstrates how cortical measurements were made at the tip of the femoral prosthesis, inferior aspect of the lesser trochanter, midway between the tip of the prosthesis and inferior aspect of the lesser trochanter, and 25 mm distal to the tip of the femoral prosthesis using a novel digital edge detection method.

were determined for inter- and intraobserver variability of classifying hips into one of the three categories based on change in cortical thickness at the tip of the prosthesis. Kappa coefficients for inter- and intraobserver variability of these measurements were 0.64 and 0.88, respectively.

We assigned more defined criteria for distal cortical hypertrophy and excessive cortical thinning with endosteal expansion. Cortical thickness at the tip of the femoral component for each hip was first plotted on a histogram (Fig. 2). Based on this plot, it was determined that hips having more than 40% increase in cortical thickness represented outliers and were therefore defined as distal cortical hypertrophy and hips having more than 20% decrease in cortical thickness represented excessive endosteal loss (Tables 1, 2). Using these criteria, 74% of hips were classified as normal femoral remodeling, 17% were classified as distal cortical hypertrophy, and 9% were classified as endosteal loss. The unusual remodeling patterns reflected 26% of the total hips in the study. Remodeling type was then statistically analyzed with regard to five patient demographic variables including sex, age at surgery, body mass index (BMI), preoperative diagnosis, and activity level. Remodeling type was also statistically analyzed with regard to initial femoral component alignment. We also investigated the time dependence of the observed remodeling changes in the proximal femur by serially plotting change in total cortical thickness versus time in the distal cortical hypertrophy (Fig. 3) and excessive endosteal loss groups (Fig. 4).

To test whether remodeling type (distal cortical hypertrophy, normal, excessive endosteal loss) is related to patient demographic variables, chi square analysis was used to test sex and age, BMI was tested with Fisher's exact test, and postoperative activity level and preoperative diagnosis were tested with Fisher's exact test. To test that remodeling type (distal cortical hypertrophy, normal, excessive endosteal loss) is related to femoral component alignment, Fisher's exact test was used. To test the time dependence of the remodeling changes, Student's t-tests were used to compare the mean change in total cortical thickness at the tip of the femoral component for the distal cortical hypertrophy and endosteal loss groups for the immediate postoperative, 2-year, 5-year, 10-year, 15-year, and 20-year followup.

Results

The first purpose of our study was to determine if remodeling patterns were related to patient demographic variables. We found no association between remodeling type and sex ($p = 0.11$), activity level ($p = 0.55$), preoperative diagnosis ($p = 0.95$), age at surgery ($p = 0.20$), or BMI ($p = 0.91$).

Fig. 2 A histogram plot of frequency of percent cortical change at the tip of the femoral prosthesis is shown. The red lines indicate the cutoff values for the endosteal loss and the distal cortical hypertrophy groups. Representative samples of each remodeling type are shown.

Table 1. Demographic characteristics of patients with total cortical hypertrophy of greater than 40% at the tip of the femoral prosthesis

Patient number	Sex	Age at surgery (years)	Diagnosis	Body mass index (kg/m ²)	Activity level [10]
1	F	60.2	DDH	24.1	2
2	M	46.1	DDH	29.6	2
3	F	43.4	DDH	36.4	2
4	F	68.2	OA	24.4	2
5	F	57.5	DDH	24.4	2
6	M	47.3	DDH	25.9	2
7	F	67.4	OA	28.0	3
8	F	64.0	OA	26.2	3
9	F	40.1	DDH	20.9	2
10	F	42.8	DDH	18.6	2
11	M	23.9	OA	28.5	2
12	F	70.2	OA	21.3	2
13	F	63.5	DDH	21.3	2
14	F	45.3	DDH	37.0	2
15	F	43.4	DDH	23.8	2
16	F	26.7	OA	21.3	2
17	F	51.4	DDH	18.6	2
18	M	31.7	Posttraumatic OA	29.8	2
19	F	41.9	DDH	26.6	2

F = female; m = male; DDH = developmental dysplasia of the hip; OA = osteoarthritis.

Therefore, femoral remodeling pattern is not related to patient demographic variables.

The second purpose of our study was to determine if remodeling patterns were related to the initial femoral component alignment. We found no association between

remodeling type and initial femoral component alignment ($p = 0.12$).

We found that distal cortical hypertrophy was predominantly an early phenomenon because there was an increase in total cortical thickness ($p = 0.001$) between the immediate

Table 2. Demographic characteristics of patients with greater than 20% loss of total cortical thickness at the tip of the femoral prosthesis

Patient number	Sex	Age at surgery (years)	Diagnosis	Body mass index (kg/m ²)	Activity level [10]
1	F	55.4	OA	44.0	2
2	F	51.3	DDH		2
3	F	51.3	DDH		2
4	F	64.0	OA	19.0	2
5	F	52.6	OA	23.7	2
6	F	52.6	OA	23.7	2
7	M	63.1	OA	24.5	2
8	F	51.4	DDH	18.6	2
9	F	49.7	DDH	28.0	2

F = female; M = male; OA = osteoarthritis; DDH = developmental dysplasia of the hip.

Fig. 3 Shown is the increase in distal cortical thickness over time in patients with distal cortical hypertrophy at the tip of the femoral prosthesis.

postoperative and 2-year followup radiographs (Fig. 3). This initial rapid increase in cortical thickness did not continue at the same rate because there was no difference among any of the later sequential time points (2–5 years, $p = 0.14$; 5–10 years, $p = 0.09$; 10–15 years, $p = 0.79$; and 15–20 years, $p = 0.17$). An example of this is shown (Fig. 5). In the group with excessive endosteal loss, there was progressive distal cortical thinning, which did not begin until after 2 years postoperatively and did not show any differences between the measured time points (immediate postoperative to 2 years, $p = 0.08$; 2–5 years $p = 0.69$; 5–10 years, $p = 0.24$; 10–15 years, $p = 0.78$; 15–20 years, $p = 0.23$) (Fig. 4).

Three cases (16%) in the distal cortical hypertrophy group showed late cancellization of the hypertrophied bone (Fig. 6). In one there was marked endosteal loss (Fig. 7), in one pronounced thickening of the entire medial and lateral cortex adjacent to the prosthesis (Fig. 8), and in one thickening of both the cortex and canal (Fig. 9).

Discussion

This study provides detailed radiographic information about the long-term bone remodeling of the proximal femur around well-functioning, cemented, stable femoral components in the THA construct. Previous studies have investigated the changes in proximal femoral geometry at mean 10.4 years [6], 13.3 years [14], and 11.5 years [17]. None of the available studies serially investigated and quantified the remodeling long-term changes of the proximal femur in well-fixed cemented THA. We therefore determined whether (1) the type of pattern of remodeling would be influenced by patient demographic variables (sex, age, BMI, activity level, preoperative diagnosis); (2) the remodeling pattern is influenced by initial femoral component alignment; and (3) the time dependence of both of the unusual remodeling patterns of distal hypertrophy and excessive endosteal loss.

We note several limitations to our study. First, we cannot ensure our findings are generalizable to other cemented

Fig. 4 Shown is the decrease in distal cortical thickness with respect to time in patients with excessive endosteal loss at the tip of the femoral prosthesis.

Fig. 5A–C Shown is an example of early distal cortical hypertrophy at (A) 6 months postoperatively, (B) 2 years postoperatively, and (C) 25 years postoperatively.

implants. Bone remodeling around cemented THA has previously been shown to be related to the stem-to-bone stiffness [21]. Therefore, our results are only applicable for the Charnley device, but given the wide application of this prosthesis, our results are particularly valuable. Second, the inherent problems with studies involving radiographic measurements include the following: magnification, rotational differences in serial radiographs, and interobserver variability of measurement. We attempted to account for these with the use of only cases with

standardized views, a single measurer, and the use of edge detection measuring techniques. Given these techniques, we believe our measurements are as accurate as can be obtained using radiographs. There is value in studying remodeling using radiographs because these are easily obtained as part of routine followup in every surgeon's practice unlike dual-energy x-ray absorptiometry [3, 5, 8, 16] or CT scans [1]. Third, we did not have serial activity levels of the patients. It is likely that these patients' activity levels fluctuated during the study period and

Fig. 6A–C Shown is an example of cancellization of distal cortical hypertrophy at (A) 2 months postoperatively, (B) 5 years postoperatively, and (C) 23 years postoperatively.

Fig. 7A–B Shown is an example of marked cortical thinning at (A) 6 months postoperatively and (B) 28 years postoperatively.

Fig. 8A–B Shown is an example of pronounced thickening of the entire medial and lateral cortex adjacent to the prosthesis at (A) 1 year postoperatively and (B) 21 years postoperatively.

likely decreased as the patients advanced in age. It is possible that, although in our analysis remodeling type was not related to activity level, the distal cortical thinning observed may have

Fig. 9A–C Shown is an example of thickening of both distal femoral cortex and expansion of endosteal canal at (A) 6 months postoperatively, (B) 15 years postoperatively, and (C) 24 years postoperatively.

been secondary to decreasing activity levels as these patients aged. Fourth, there are multiple preoperative diagnoses used in this study, some of which place constraints on the position in which the implant can be placed. This may provide a confounding variable of implant position to preoperative diagnosis; however, we believe this was accounted for by ensuring similar rotational alignment on serial radiographs as well as investigating the impact of component alignment on remodeling. Fifth, we did not evaluate remodeling changes in hips that underwent femoral revisions. Because only well-fixed hips were evaluated, we were unable to make any conclusions regarding the effects of these remodeling changes on the long-term stability of the implants.

We classified 74% of hips as normal femoral remodeling, 17% as distal cortical hypertrophy, and 9% as endosteal loss. These values are slightly different than those in the study of Kobayashi et al. [14], which reported 29% distal thickening and 10% excessive cortical thinning, which was based on gross inspection of serial radiographs. The difference in values between these two study groups is likely explained by the different criteria used to define cortical thickening and loss as well as the Asian versus the white cohorts.

Distal cortical hypertrophy occurred predominantly in the first 2 years postoperatively and then progressed at a much slower rate thereafter (Fig. 3). In contrast, endosteal loss did not begin until 2 years postoperatively and continued throughout the lifetime of the implant without a distinct time period when a majority of the changes occurred (Fig. 4).

Previous authors have also described the progressive nature of the cortical thinning and endosteal canal expansion observed in this study [6, 10, 17]. Newer cementless implants have also shown distal hypertrophy to be an early phenomenon and endosteal loss to be progressive [2]. This study provides a comparison for timing of distal cortical hypertrophy with other cemented hip implants as well as other newer cementless femoral implants.

An interesting and unexpected finding within the group of hips that showed distal cortical hypertrophy is that three hips (16%) showed late cancellization of the hypertrophied bone after 15 years of radiographic followup. It is unclear as to the mechanism responsible for this late cancellization but it may be related to decreased activity later in life in these patients or the development of generalized osteoporosis. None of the findings we have reported, however, had any effect on component stability.

Our study expands on the previous literature by determining that preoperative patient demographic variables are not related to the observed long-term changes in the proximal femur around well-fixed cemented Charnley THA. The initial femoral component alignment or patient demographic factors were not related to the remodeling changes and distal cortical hypertrophy was predominantly an early phenomena, whereas cortical thinning occurred later and in a more progressive manner. Our observations also confirm the variability in long-term femoral remodeling around well-fixed and well-functioning cemented THA constructs.

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