Femoral Revision with an Extensively Hydroxyapatite-Coated Femoral Component

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Published online: 1 December 2007
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Abstract Between December 1996 and April 2003, 26 consecutive femoral component revisions in 24 patients were performed with an extensively hydroxyapatite-coated femoral stem. Two patients were lost to follow-up, and two patients died of unrelated causes. Of the 22 femoral revisions in 20 patients, there was a 0% incidence of mechanical loosening at average follow-up of 3.2 years (2–6.3 years). The Harris Hip Score improved from 59 (36 to 83) to 95 (84 to 100) postoperatively ($p < 0.001$). Rate of revision was 18.2% (4.5% for sepsis, 9.1% for instability, and 4.5% for polyethylene wear). All 22 femoral components had evidence of bone ingrowth. The extensively coated hydroxyapatite stem in this series produced excellent clinical results with a low incidence of thigh pain (4.5%) and severe stress shielding (4.5%).

Key words total hip arthroplasty · femoral revision · hydroxyapatite coating

Introduction

Femoral component revision in total hip arthroplasty is often complicated by insufficient proximal bone stock. The remaining bone is inadequate to provide structural support, osteogenic potential for bone ingrowth, or a surface that

allows for cement interdigitation. For these reasons, revision stems that are cemented, or rely on proximal fixation, have historically provided disappointing result [1–8]. One strategy in managing this problem is to use an extensively porous-coated stem that bypasses the deficient segment of proximal femur and takes advantage of distal fixation to healthy diaphyseal bone.

The use of extensively porous-coated stems has provided predictable, stable, long-term fixation with mechanical loosening in as few as 1 to 11% of patients [5, 9–11]. However, despite excellent clinical performance, radiographic evaluation of extensively porous-coated cobalt chrome stems has shown fibrous ingrowth in approximately 15% of patients [5, 9, 11, 12]. Furthermore, Moreland and Bernstein [5] reported an increased incidence of thigh pain in patients with fibrous ingrowth. Studies have shown that the incidence of severe stress shielding with fully porous-coated stems ranges from 6 to 19.5% [5, 9, 11].

Recently, calcium phosphate ceramics such as hydroxyapatite (HA) have been employed to enhance fixation of cementless stems by encouraging bone ingrowth especially in regions where bone gaps exist. Results of HA-coated femoral stems in the primary total hip arthroplasty have been excellent; however, little has been published on its use in the revision setting [13, 14]. The HA-coated revision stem has the potential for improved fixation with less fibrous ingrowth, less thigh pain, and less stress shielding.

This study reviews the experience of a single surgeon (BJN) using a fully HA-coated femoral stem for femoral revisions in patients with moderate to severe proximal femoral bone loss (Restoration HA, Stryker Howmedica Osteonics, Allendale, NJ). The implant design consists of a titanium, non-modular, cylindrical stem treated with extensive arc deposition and coated with hydroxyapatite. To our

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knowledge, there is only one study reporting on the early clinical and radiographic results with use of this stem [15]. The results of that study are encouraging. We hypothesized that an extensively HA-coated stem could provide improved radiographic results at intermediate follow-up and possibly less thigh pain and stress shielding.

Materials and methods

Between December 1996 and April 2003, a single surgeon performed 26 consecutive femoral component revisions in 24 patients using an extensively HA-coated femoral stem (Restoration HA, Stryker Howmedica Osteonics). Two patients were lost to follow-up, and an additional two patients died of causes unrelated to their surgery within the study period. Both patients who died during the study period had 12 months of follow-up. At that time, they each required a revision to a constrained liner for recurrent dislocations, but ultimately achieved a stable implant. These patients were excluded from the final analysis. Two patients underwent bilateral revisions. This resulted in 22 femoral revisions in 20 patients who made up the final study cohort. These patients were retrospectively reviewed.

The average age was 60 years (range, 31–84 years). There were 11 men and 9 women. The average length of follow-up was 3.2 years (minimum 2 years, maximum 6.3 years). The diagnosis at the time of index total hip arthroplasty was osteoarthritis in 15 hips, post-traumatic osteoarthritis in three hips, juvenile rheumatoid arthritis in two hips, rheumatoid arthritis in one hip, and avascular necrosis in one. The diagnosis at time of revision was aseptic femoral component loosening in 17 hips and infection requiring explantation in the remaining five. Aseptic and septic loosening were both included in the study, as the main study question was whether this implant can achieve stable fixation in the setting of proximal femoral bone loss. At the time of index surgery, all patients with a prior infection had negative cultures upon hip aspiration. These groups were analyzed together and separately. Of the 22 femoral components revised, 15 were cemented, six were uncemented, and one was a surface replacement with massive proximal osteolysis (Fig. 1). Only 2 of the 22 femoral components revised were from previous revisions, one an infected well-fixed uncemented stem and the other a loose proximal coated revision stem. The average time to revision from index arthroplasty for the remaining 20 femoral components was 8.7 years (minimum 1 year, maximum 27 years). The acetabular component was revised in 12 hips, the polyethylene liner was exchanged in three hips, and no changes were made to the cup or liner in seven hips.

A standard posterolateral approach was used in 18 hips. An extended trochanteric osteotomy was used in four hips, including three with infection to facilitate implant removal. Only four patients were treated with femoral bone grafting. In one patient, a cortical strut graft was placed over a perforation that occurred at the time of cement removal. In three patients, morselized femoral head allograft was

Fig. 1. **a** Preoperative radiograph of a 34-year-old male with aseptic loosening of a surface replacement femoral component with extensive proximal osteolysis. **b** Postoperative x-ray of the revised hip demonstrates 13 mm of increased lateral offset compared to the contralateral hip and a 3-mm increase in leg length

impacted into the proximal metaphysis, and one of the three also had a cortical strut graft placed for an intraoperative diaphyseal fracture. Of note, most patients received no proximal bone graft.

Patients were clinically evaluated both preoperatively and postoperatively at regular follow-up intervals using the Harris Hip Score [16, 17]. Patients were specifically questioned for the presence of thigh pain. Complications including intraoperative or postoperative fracture, dislocation, infection, and the need for reoperation were also noted.

Standard anterior-posterior and lateral radiographs taken preoperatively and postoperatively at regular follow-up intervals were evaluated. The preoperative bone deficiency was evaluated using the classification system described by Mallory [18]. Using this classification system, the preoperative femoral bone loss was type I in two hips, type II in four, type IIIA in one, and type IIIB in 15. Postoperative radiographs were evaluated for signs of osseous integration using the method described by Engh et al. [19]. Specifically, each radiograph was evaluated for subsidence, pedestal formation, osteolysis, calcar resorption, osseous integration, presence of radiolucent lines, percent of canal fill by the implant, and presence of hypertrophied bone at the tip of the implant.

Stress shielding was subjectively rated by comparing the preoperative and postoperative radiographs according to the criteria used by Moreland and Moreno [11]. In these criteria, minimal stress shielding is judged to be present

when little to no change in cortical density and thickness could be observed. Moderate stress shielding was considered to be a significant and obvious loss of cortical density and thickness but not of a striking degree. Severe stress shielding was a major, striking, and impressive degree of bone loss. Femoral cortical index, which has been shown to correlate with stress shielding, was also determined on the 6-week postoperative radiograph [20, 21].

The overall alignment of the implant was determined radiographically by comparing the central axis of the implant to the central axis of the femoral shaft. Leg length discrepancies were measured by comparing the perpendicular distance from the inferior border of the ischial tuberosity to the top of the lesser trochanter. Lateral offset was determined by measuring the perpendicular distance from the teardrop to the femoral head center and the perpendicular distance from the femoral head center to the central axis of the femoral shaft. The lateral offset was determined in cases in which the contralateral hip was native. All radiographic measurements and ratings were determined by two orthopedic surgeons (LG and BN). When there were discrepancies between the two evaluations, a consensus was reached between the investigators.

Means, standard deviations, minimum, and maximum values were calculated for all continuous variables, while frequency counts and percentages were calculated for discrete variables. Inferential analysis consisted of Mann–Whitney tests for non-parametric data for continuous outcomes and χ^2 test or Fisher's exact test for discrete outcomes, as appropriate. Spearman's correlation coefficients were calculated to determine correlations between continuous measurements. A critical p value of 0.05 was used to determine statistical significance. No corrections were made for multiple comparisons. All analyses were performed using SPSS for Windows version 13.0 (Chicago, IL).

Results

The average preoperative Harris Hip Score was 59 points (minimum 36, maximum 83), which improved to 95 points (minimum 84, maximum 100) at latest follow-up. ($p < 0.001$) Pain relief was excellent (Harris hip pain score of 44) in 16 hips and good in the remaining six (pain score of 40). Only three patients developed thigh pain. In two of the three patients, the pain resolved. This included one patient that developed a stress fracture in the medial femoral cortex through a previous screw hole opposite the distal site of an extended trochanteric osteotomy that was not united distally. The patient's pain resolved after a period of protected weight bearing. Only one patient had persistent thigh pain at latest follow-up, which was mild, intermittent, and did not limit activity.

Radiographic evidence of bone ingrowth was achieved in all 22 stems. None of the stems exhibited fibrous ingrowth. Cortical spot welds were observed in all stems on both the A/P and lateral radiographs occurring in an average of 7.9 Gruen zones (minimum 6, maximum 11) for

each stem. There was no significant correlation between the number of spot welds and patient age ($p = 0.32$), gender ($p = 0.19$), percentage canal fill ($p = 0.32$), cortical index ($p = 0.07$), or preoperative bone stock ($p = 0.11$). Femoral prosthetic subsidence was not observed.

Twenty-one of the stems were 205 mm in length; one stem used in the patient with a failed surface replacement was 155 mm in length (Fig. 1). The average stem diameter was 16.4 mm (minimum 12 mm, maximum 20 mm), and the average percentage of canal fill was 92% (minimum 84%, maximum 100%). Radiolucencies were noted in at least one Gruen zone in four hips. All were less than 2 mm, incomplete, and non-progressive. New evidence of osteolysis was not observed in any of the follow-up hip radiographs. Interestingly, four hips (18%) in which bone graft was not used had radiographic evidence of resolution of proximal metaphyseal osteolytic lesions (Fig. 2). Four hips had some degree of stress shielding (18%). Two were considered minor, one moderate, and one severe (Fig. 3). Stress shielding was shown to have a significant correlation with the cortical index ($p = 0.02$). The two patients with significant stress shielding had severe (Mallory IIIB) preoperative bone loss. However, stress shielding was not correlated with preoperative bone loss ($p = 0.38$). Stress shielding was also not shown to correlate with stem diameter ($p = 0.56$), percentage of canal fill ($p = 0.91$), patient age ($p = 0.53$), or gender ($p = 0.24$). Cortical hypertrophy at the tip of the implant was present in ten hips (45%). Pedestal formation was not observed in any hip radiographs.

The overall femoral stem alignment was neutral in 20 hips (90.9%) and in one degree of varus in two hips. For eleven patients with a native hip on the contralateral side, the difference in lateral offset was determined. The average lateral offset was increased 8.2 mm (Fig. 1). In ten patients, the offset was increased from 2 to 16 mm, and in one patient, the lateral offset was decreased by 5 mm compared to the opposite native hip. Leg length discrepancy was less than 7 mm in 16 hips (72.7%). In the six hips (27.3%) with greater than 7-mm difference, the revised hip was shorter in three (8, 8, and 12 mm) and longer in three (10, 10, and 14 mm).

Intraoperative femoral fractures occurred in seven hips (31.8%). Four fractures (18.2%) were small cracks occurring in the deficient proximal bone. Three were identified at the time of implant and/or cement removal and treated with cerclage wiring and no change in postoperative management. One was recognized postoperatively and successfully treated with protected weight bearing. There were three diaphyseal fractures (13.6%) that occurred with seating of the femoral component. Two of the fractures were recognized and treated with cerclage wiring, one of which required a cortical strut allograft. One of the three diaphyseal fractures was recognized postoperatively and successfully treated with protected weight bearing.

Postoperative femoral fractures occurred in two patients (9.1%), one involving the greater trochanter and one the aforementioned stress fracture. All postoperative fractures were successfully treated non-operatively.

Fig. 2. **a** Preoperative radiograph of a hip in a 58-year-old male with aseptic loosening of the femoral component and extensive osteolysis. **b** Immediate postoperative radiograph reveals revision with an extensively HA-coated femoral component. There is persistence of

the lytic bone lesions which were not bone-grafted. **c** Five-year follow-up radiograph demonstrates resolution of the lytic lesions in the proximal medial metaphysis

Dislocation occurred in four hips (18.2%) requiring revision to a constrained acetabular liner in two cases (9.1%). Acetabular component revision versus retention ($p=0.59$), elevated versus standard liner ($p=0.45$), leg length ($p=0.17$), and lateral offset ($p=0.86$) were not shown to correlate with dislocation. There were no revisions for femoral loosening. There was one revision for sepsis (4.5%). The patient required explantation of the femoral component due to infection 4.3 years after revision. This patient had a diagnosis of juvenile rheumatoid arthritis and underwent the index revision surgery for aseptic loosening. At the time of surgery, the implant was found to be solidly fixed. Explantation was facilitated with an extended trochanteric osteotomy (Fig. 4). After the infection had been eradicated, another restoration HA fully porous-coated femoral component (250 mm) was reimplanted and that patient had an excellent outcome (Harris Hip Score of 90 points) with no

evidence of loosening or recurrence of infection at final follow-up. There was another revision for excessive polyethylene wear of the acetabular liner in which a new liner was cemented into a well-fixed acetabular shell. Therefore, the overall revision rate was 18.2%, (0% for mechanical loosening, 4.5% for sepsis, 9.1% conversion to constrained liner for recurrent instability, and 4.5% liner exchange for excessive polyethylene wear).

There were no differences between patients who underwent the index revision for aseptic or septic loosening in regards to preoperative Harris Hip ($p=0.74$) or bone stock deficiency ($p=0.48$). Likewise, there were no differences in terms of postoperative Harris Hip Score or the presence of stress shielding, spot welding, lateral offset, leg length discrepancy, intraoperative or postoperative fracture, dislocation, or the need for revision surgery ($p>0.05$ for all variables).

Fig. 3. **a** Preoperative radiograph in a 57-year-old male demonstrates aseptic loosening of the total hip replacement with significant femoral cortical thinning. **b** Immediate postoperative radiograph of the revised

hip. **c** The radiograph at last follow-up demonstrates severe stress shielding, especially of the medial cortex proximal to the cerclage cable

Fig. 4. **a** Preoperative radiograph of a 35-year-old female with JRA 4 years after R revision THR with a restoration fully HA-coated stem. Preoperative aspiration confirmed bilateral infections. **b** Postoperative radiograph after staged removal of bilateral THRs. **c** Postoperative radiograph 2 years after successful reimplantation of bilateral hips with fully HA-coated restoration femoral components

Discussion

Revision total hip arthroplasty is often complicated by moderate or severe proximal femoral bone deficiency. In this setting, attempts at revision with cemented implants or uncemented implants that rely on proximal fixation have shown discouraging clinical results [1–8, 21].

Fully porous-coated femoral stems allow the surgeon to bypass the area of deficiency and rely on distal fixation in healthy diaphyseal bone. Several studies have demonstrated superior fixation with fully porous-coated stems. Engh et al. [22] were among the first to demonstrate reliable bone fixation in the revision setting with extensively coated fem-

oral components. They reported on 166 cementless femoral revisions using the anatomic medullary locking femoral component with 1% mechanical loosening at 4.4 years of follow-up. Lawrence et al. [10] reported on 174 uncemented revisions with an average follow-up of 7.4 years and a mechanical failure rate of 6.9%. Using the same femoral component, Moreland and Bernstein [5] reported a 2.3% failure rate for loosening in 175 hips followed for an average 5 years with 17.2% of the stems exhibiting fibrous ingrowth. In a similar study with longer follow-up, Moreland and Moreno [11] reported a 4% loosening rate with 137 hips and an average follow-up of 9.3 years and 14% of stems exhibiting fibrous ingrowth. Krishnamurthy et al. [9] reviewed 297 femoral revisions with the anatomic medullary locking femoral component with a minimum 5-year and an average 8.3-year follow-up and found a mechanical failure rate of only 2.4%. However, 15.6% of the stems exhibited fibrous ingrowth. A follow-up to this study with a minimum 10-year follow-up reported a mechanical loosening rate of 4.1% and fibrous ingrowth in 13.9% of stems [12].

The experience with extensively porous-coated titanium stems suggests even lower rates of mechanical loosening and less fibrous ingrowth. Head et al. [23] reported a 13-year survival rate of 99% with mechanical failure as an endpoint and no fibrous ingrowth in 1,179 revision hips using a titanium cementless calcar replacement stem. Trikha et al. [24] reported a 10-year survival rate of 100%, all with bony ingrowth, in 120 femoral revisions with a fully hydroxyapatite-coated titanium femoral stem (JRI Furlong HAC coated, JRI Instrumentation Ltd., London, UK). Raman et al. [25] also showed 100% survival at 13 years with a 94% incidence of osseointegration in 86 femoral revisions with the same JRI HAC femoral stem. In the only other study to evaluate the osteonics restoration HA-coated femoral stem, Crawford et al. [15] found an overall mechanical failure rate of 2% in 49 femoral revisions. They did not comment on the presence or absence of fibrous ingrowth. The results of this study compare favorably with the studies cited, demonstrating bone ingrowth in all 22 femoral components with no fibrous ingrowth and no mechanical loosening at early to intermediate follow-up.

The incidence of thigh pain in this study also compares favorably with the literature. Significant thigh pain has been reported to occur in 9 to 10% of cementless revisions with fully porous-coated cobalt chrome stems [9, 11]. Thigh pain has been shown to be significantly increased in patients with fibrous rather than bone ingrowth [11]. In this study only, one patient (4.5%) had persistent thigh pain at latest follow-up, which was mild, intermittent, and did not limit activity.

However, whereas studies on femoral revision with fully porous-coated implants have provided the most promising results, there are concerns regarding stress shielding. The clinical significance of stress shielding remains controversial. Engh and Bobyn [20], in a comparative study, found no correlation between proximal stress shielding and stem fracture, periprosthetic fracture, loosening, increased difficulty of revision, or increased susceptibility to osteolysis. Bone remodeling in the proximal femur occurs with all

types of femoral implants, whether cemented or uncemented [26]. However, radiographically significant stress shielding has been shown to occur more frequently with fully porous-coated femoral implants [27].

Severe stress shielding has been reported in 6 to 19.5% of revisions with extensively porous-coated cobalt chromium stems [5, 9, 12]. In this series, stress shielding did not occur in 86.5% of patients. In only one patient (4.5%) was the stress shielding severe and that was related to a low preoperative cortical index (Fig. 3). This patient remains asymptomatic. Additional factors influencing the extent of stress shielding include age, gender, stem size, and preoperative bone quality [5, 9, 27]. We did not find a correlation between the presence of stress shielding and the distal stem diameter, age, or gender. Stem material may also influence the incidence and extent of stress shielding. Most of the clinical series reporting higher rates of stress shielding have been with femoral components made of cobalt chrome [5, 9, 11, 27]. Titanium, with a lower modulus of elasticity as well as the affinity of bone for titanium, has been associated with lower rates of stress shielding [28]. The fact that the restoration stem is titanium might account for the low incidence of stress shielding in this series, but another consideration is the hydroxyapatite coating. Crawford et al. [15] reported that 22% of patients exhibited some degree of stress shielding; however, none of them were considered severe. Raman et al. [25] confirmed these findings, reporting 28% rate of stress shielding with none categorized as severe. They concluded that HA-coated, fully porous femoral stems can perform similarly to implants that are not HA-coated and can reduce the incidence of stress shielding.

Hydroxyapatite-coated implants have been developed in an attempt to further induce bone ingrowth. Karrholm et al. [29] showed that HA-coated stems enhance early fixation as evidenced by less subsidence when compared to cemented or fully porous-coated stems. Coathup et al. [30] more recently showed that HA-coated implants have more bone ingrowth and have more even distribution of bone over the surface of the implant as compared to proximally coated implants that had been either plasma-sprayed or grit-blasted. Bauer et al. [31] and Hardy et al. [32] performed histopathologic studies of HA-coated stems that had been retrieved from patients during postmortem examinations. Both studies found newly formed bone overlying the HA coating with new trabeculae bridging to the endosteal layer consistent with biological osseointegration. An interesting observation made in this study was the overwhelming presence of spot welding around the femoral implant. Spot welding was observed in more than four Gruen's zones on the antero-posterior radiograph in 82% of cases and in more than four Gruen zones on the lateral radiograph in 60%. The extent of bone ingrowth and the absence of fibrous ingrowth in this series of patients might be attributable to the HA coating. Additionally, four patients exhibited remarkable resolution of lytic lesions in the medial metaphysis on x-ray despite having received no cancellous bone graft (Fig. 2). This supports previous findings by Trikha et al. [24] who reported bone reconstitution in 51% of Gruen's zones after revision with a

fully hydroxyapatite-coated titanium femoral stem. This phenomenon may be a response to the HA coating.

The most common complication in this study was periprosthetic fracture occurring in nine patients (40.9%). The majority of these fractures were intraoperative (31.8%). In four patients (18.2%), the intraoperative fractures consisted of small fractures in the calcar that occurred at the time of implant and or cement removal. However, three fractures (13.6%) were diaphyseal fractures that occurred with seating of the femoral component. Two of the three diaphyseal cortical fractures were recognized immediately and treated with cerclage cables and allograft struts. The other was recognized postoperatively and treated with protected weight bearing. All fractures healed uneventfully without any untoward effect on clinical or radiographic outcome.

Another common complication was postoperative dislocation. In this study, dislocation occurred in four hips (18.2%), with two hips requiring conversion to a constrained liner (9.1%). No significant correlation was found between dislocation and acetabular revision, the use of elevated liners, or differences in leg length or lateral offset. Crawford et al. [15], using the same femoral component, did not report the incidence of dislocation. One possible reason for the high dislocation rate may have to do with circular neck and long taper design of the restoration stem. Barrack et al. [33] compared two different neck designs both clinically and with computer modeling. Design I had a circular cross-section and a long taper, and design II had a trapezoidal cross-section with a short taper. Design I had 32% greater cross-sectional area and 76% less arc of motion by computer modeling [33]. Although not significant, clinical dislocation occurred in 15.4% of the hips with design I ($n=52$) and only 4.5% of hips with design II ($n=46$) [33].

One of the limitations of a non-modular stem is that the proximal geometry is dictated by the size of the stem required distally. Therefore, the distal stem diameter required to obtain diaphyseal fixation may result in using a stem with a proximal geometry that increases the patient's normal anatomic lateral offset and neck length. This situation may result in the potential for an increase in lateral offset and, in some cases, leg length. In this study, lateral offset was increased an average of 8.2 mm in 10 of 11 revised hips compared to the native contralateral hip (Fig. 1). Although there was no effect on the clinical result in this cohort of patients, a significant increase in lateral offset may result in a functional leg length discrepancy by creating an abduction contracture. Actual leg length was restored to within 7 mm in 16 hips (72.7%) as measured radiographically. In six hips (27.3%), there was a difference of greater than 7 mm (8–14 mm), with the revised leg lengthened in three and shortened in three. One patient required the use of a lift in the opposite shoe for 14 mm of lengthening of the operated leg.

There are several limitations in this study. First, this study has a relatively short follow-up period of just more than 3 years. Further studies are needed to determine if these implants will continue to perform well with long-term follow-up. However, previous authors have documented

that stress shielding usually occurs in the first couple years and then stabilizes [11, 25]. Therefore, very little progression of shielding should be expected in this cohort with longer follow-up. Second, the radiographic assessments with regard to stress shielding made in this study are subjective. Whereas some authors have questioned the validity of subjective radiographic assessments, others have found them to be satisfactory [11, 12, 34]. Additionally, bone density and computed tomography scans were not used to provide corroborative evidence of stress shielding.

At a relatively short-term follow-up, fully hydroxyapatite-coated femoral stems are an effective tool in revision total hip replacement with moderate to severe proximal femoral deficiency. This is evidenced clinically by the statistically significant improvement in Harris Hip Scores postoperatively as compared to preoperatively. It is also evidenced radiographically by the extent of spot welding seen despite little proximal bone for fixation.

References

- Berry D, Harmsen W, Ilstrup D, et al. (1995) Survivorship of uncemented proximally porous-coated femoral components. *Clin Orthop Relat Res* 319:168–177
- Katz R, Callaghan J, Sullivan P, et al. (1995) Results of cemented femoral revision total hip arthroplasty using improved cementing techniques. *Clin Orthop Relat Res* 319:178–183
- Kavanagh B, Ilstrup D, Fitzgerald R (1985) Revision total hip arthroplasty. *J Bone Jt Surg* 67-A(4):517–526
- Malkani A, Lewallen D, Cabanela M, et al. (1996) Femoral component revision using an uncemented, proximally coated, long-stem prosthesis. *J Arthroplasty* 11(4):411–418
- Moreland J, Bernstein M (1995) Femoral revision hip arthroplasty with uncemented, porous-coated stems. *Clin Orthop Relat Res* 319:141–150
- Mulliken B, Rorabeck C, Bourne R (1995) Uncemented revision total hip arthroplasty: a 4- to 6-year review. *Clin Orthop Relat Res* 325:156–162
- Mulroy W, Harris W (1996) Revision total hip arthroplasty with use of so-called second-generation cementing techniques for aseptic loosening of the femoral component. *J Bone Jt Surg* 78-A(3):325–330
- Pellicci P, PD Wilson J, Sledge C, et al. (1985) Long-term results of revision total hip replacement. *J Bone Jt Surg* 67-A(4):513–516
- Krishnamurthy A, MacDonald S, Paprosky W (1997) 5- to 13-year follow-up study on cementless femoral components in revision surgery. *J Arthroplasty* 12no. 8, 839–847
- Lawrence J, Engh C, Macalino G (1993) Revision total hip arthroplasty: long-term results without cement. *Orthop Clin North Am* 24no. 4, 635–644
- Moreland J, Moreno M (2001) Cementless femoral revision arthroplasty of the hip. *Clin Orthop Relat Res* 393:194–201
- Paprosky WG, Greidanus NV, Antoniou J (1999) Minimum 10-year results of extensively porous-coated stems in revision hip arthroplasty. *Clin Orthop Relat Res* 369:230–242
- Dumbleton J, Manley M (2004) Hydroxyapatite-coated prostheses in total hip and knee arthroplasty. *J Bone Jt Surg* 86-A(11):2526–2540
- Lilikakis A, Vowler S, Villar R (2005) Hydroxyapatite-coated femoral implant in metal-on-metal resurfacing hip arthroplasty: minimum of two years follow-up. *Orthop Clin North Am* 36no. 2, 215–222
- Crawford C, Malkani A, Incavo S, et al. (2004) Femoral component revision using an extensively hydroxyapatite-coated stem. *J Arthroplasty* 19(1):8–13
- Mahomed N, Arndt D, McGrory B, et al. (2001) The Harris Hip Score: comparison of patient self-report with surgeon assessment. *J Arthroplasty* 16(5):575–580
- Soderman P, Malchau H (2001) Is the Harris Hip Score System useful to study the outcome of total hip replacement. *Clin Orthop Relat Res* 384:189–197
- Mallory T (1988) Preparation of the proximal femur in cementless total hip revision. *Clin Orthop Relat Res* 235:47–60
- Engh C, Massin P, Suthers K (1990) Roentgenographic assessment of the biologic fixation of porous-surfaced femoral components. *Clin Orthop Relat Res* 257:107–128
- Engh C, Bobyn J (1985) Biological fixation in total hip arthroplasty, technique for primary surgery. Thorofare, SLACK Inc.
- Engh CA, Jr., Young AM, Engh CA, Sr., et al. (2003) Clinical consequences of stress shielding after porous-coated total hip arthroplasty. *Clin Orthop Relat Res* 417:157–163
- Engh CA, Glassman AH, Griffin WL, et al. (1988) Results of cementless revision for failed cemented total hip arthroplasty. *Clin Orthop Relat Res* 235:91–110
- Head WC, Emerson RH, Jr., Higgins LL (2001) A titanium cementless calcar replacement prosthesis in revision surgery of the femur: 13-year experience. *J Arthroplasty* 16no. 8 Suppl 1, 183–187
- Tripathi SP, Singh S, Raynham OW, et al. (2005) Hydroxyapatite-ceramic-coated femoral stems in revision hip surgery. *J Bone Jt Surg Br* 87-B(8):1055–1060
- Raman R, Kamath RP, Parikh A, et al. (2005) Revision of cemented hip arthroplasty using a hydroxyapatite-ceramic-coated femoral component. *J Bone Jt Surg Br* 87-B(8):1061–1067
- Maloney WJ, Sychterz C, Bragdon C, et al. (1996) The Otto Aufranc Award. Skeletal response to well fixed femoral components inserted with and without cement. *Clin Orthop Relat Res* 333:15–26
- Engh CA, Bobyn JD (1988) The influence of stem size and extent of porous coating on femoral bone resorption after primary cementless hip arthroplasty. *Clin Orthop Relat Res* 231:7–28
- Emerson RH, Jr., Head WC, Higgins LL (2003) Clinical and radiographic analysis of the Mallory–Head femoral component in revision total hip arthroplasty. A minimum 8.8-year and average eleven-year follow-up study. *J Bone Jt Surg Am* 85-A(10):1921–1926
- Karrholm J, Malchau H, Snorrason F, et al. (1994) Micromotion of femoral stems in total hip arthroplasty: a randomized study of cemented, hydroxyapatite-coated, and porous coated stems with reontgen stereophotogrammetric analysis. *J Bone Jt Surg* 76-A(11):1692–1705
- Coathup M, Blunn G, Flynn N, et al. (2001) A comparison of bone remodelling around hydroxyapatite-coated, porous-coated and grit blasted hip replacements retrieved at post-mortem. *J Bone Jt Surg* 83-B(1):118–123
- Bauer T, Geesink R, Zimmerman R, et al. (1991) Hydroxyapatite-coated femoral stems: histological analysis of components retrieved at autopsy. *J Bone Jt Surg* 73-A(10):1439–1452
- Hardy D, Frayssinet P, Guilhem A, et al. (1991) Bonding of hydroxyapatite-coated femoral prosthesis: histopathology of specimens from four cases. *J Bone Jt Surg* 73-B(5):732–740
- Barrack RL, Butler RA, Laster DR, et al. (2001) Stem design and dislocation after revision total hip arthroplasty: clinical results and computer modeling. *J Arthroplasty* 16(8 Suppl 1):8–12
- Engh C, McAuley J, Sychterz C, et al. (2000) The accuracy and reproducibility of radiographic assessment of stress-shielding. *J Bone Jt Surg* 82-A(10):1414–1420