Pyrolytic Carbon Endoprosthetic Replacement for Osteonecrosis and Femoral Fracture of the Hip

A Pilot Study

Thomas L. Bernasek MD, Jennifer L. Stahl BS,
Derek Pupello MBA

Received: 21 January 2008 / Accepted: 18 March 2009 / Published online: 11 April 2009
© The Association of Bone and Joint Surgeons 2009

Abstract Hemiarthroplasty in young patients has the potential for eliminating bearing wear, but has the disadvantage of cartilage wear. Low-temperature isotropic (LTI) pyrolytic carbon reportedly reduces cartilage wear in canine hemiarthroplasties. We therefore initiated a study in humans when it was released for human use. However, we observed failures in some patients. We therefore document and report the high failure rate observed in a subset of patients treated with an LTI pyrolytic carbon femoral head for osteonecrosis. We conducted a prospective pilot study of 17 patients treated with a titanium stem and an LTI pyrolytic carbon femoral head bearing surface for unipolar hemiarthroplasty for either femoral neck fracture (10 patients) or osteonecrosis (seven patients). One of 10 patients in the fracture group underwent conversion to THA as a result of arthritic progression compared with six of seven patients with osteonecrosis who underwent conversion to THA as a result of acetabular wear and severe groin pain. In this small series, patients with osteonecrosis

had a higher rate of revision compared with the patients treated for femoral neck fracture.

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

Introduction

Although hemiarthroplasty is a well-established treatment for femoral neck fractures [22, 32], it has produced mixed results for treatment of osteonecrosis (ON) of the hip [1–5, 21, 32, 39]. Treatment options for patients with ON include arthrodesis [24], artificial and biologic surface replacement [1], core decompression with nonvascularized or vascularized bone grafting [28, 31, 40], THA [4, 5], and hemiarthroplasty [1, 3, 21]. Controversy exists regarding whether THA or hemiarthroplasty should be the principal treatment for patients with Ficat and Arlet [15] Stage III ON of the femoral head [1–5, 14, 21, 39].

Hemiarthroplasty in younger patients has the potential advantage of eliminating bearing surface wear [1–5, 21, 30, 39] and is easily revisable [10]; however, the reported success rates have ranged from 64% to 87% [10, 21, 25, 26, 49]. Reports indicate hemiprosthetic failure is likely the result of accelerated acetabular erosion resulting in groin pain postoperatively [5, 10, 21]. However, disadvantages of hemiarthroplasty include incidence of groin pain (range, 12%–42%) [4, 21, 26, 27, 44] and head migration (range, 8%–23%) [4, 21, 44], whereas THA in younger patients is associated with early failure owing to bearing wear and osteolysis [12, 35]. Hemiarthroplasty in younger patients has the potential advantage of eliminating bearing surface wear [1–5, 21, 30, 39] and is easily revisable [10]; however, the reported success rates have ranged from 64% to

Each author certifies that he or she has no commercial associations (eg, consultancies, stock ownership, equity interest, patent/licensing arrangements, etc) that might pose a conflict of interest in connection with the submitted article.

Each author certifies that his or her institution has approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained.

T. L. Bernasek (✉)
Adult Reconstruction Service, Florida Orthopaedic Institute,
13020 Telecom Parkway North, Tampa, FL 33637, USA
e-mail: tbernasek@floridaortho.com

J. L. Stahl, D. Pupello
Foundation for Orthopaedic Research and Education,
13020 Telecom Parkway North, Tampa, FL 33637, USA

87% [10, 21, 25, 26, 49]. Reports indicate hemiprosthetic failure is likely the result of accelerated acetabular erosion resulting in groin pain postoperatively [5, 10, 21].

LTI pyrolytic carbon is a biomaterial that has been used extensively in cardiovascular and orthopaedic prosthetics such as heart valves [50] and metacarpal and metatarsal joint replacements [46]. The use of this material in phalangeal joint replacement has been associated with decreased pain, increased range of motion, and a 10-year survival rate of 81.4% [6, 38, 43]. Canine hip studies using LTI pyrolytic carbon hemiarthroplasty suggest decreased acetabular cartilage wear compared with metal heads [8, 29, 30, 47]. One study [8] examined cartilage degeneration in 45 dogs that underwent hemiarthroplasty with three articulating surface materials: (1) LTI pyrolytic carbon; (2) cobalt-chromium-molybdenum alloy; and (3) titanium alloy. The LTI pyrolytic carbon group had a 92% acetabular cartilage survival probability, whereas the cobalt-chromium-molybdenum and titanium alloy groups had only a 20% probability for survival. Another study [23] evaluated the effect of pyrolytic carbon and cobalt-chromium hemiarthroplasties on a surgically created full-thickness defect in the knee cartilage of adult Beagles. One year after implantation, cartilage surface cracks were seen in 100% of the metal implants compared with 14% in the carbon specimens. In addition, fibrocartilage regeneration was seen in 86% of the carbon implants and in only 25% of the metal ones [23]. In 1990, An LTI pyrolytic carbon femoral head hemiarthroplasty was approved for human use and incorporated into our practice for treatment of patients with femoral neck fractures or ON of the femoral head. Based on the animal studies, we anticipated we eventually would see low wear rates, however we began to see failures in some patients.

The purpose of this study therefore was to document and report the high failure rate observed in the subset of patients treated with an LTI pyrolytic carbon femoral head for ON.

Materials and Methods

We conducted a prospective pilot study of 17 patients treated with a titanium stem and an LTI pyrolytic carbon femoral head bearing surface for unipolar hemiarthroplasty for either femoral neck fracture (10 patients) or ON (seven patients) between February 1990 and May 1993. The 10 patients with a fracture were a mean age of 75.5 years (range, 62–94 years) and the seven patients with ON were a mean of 35.1 years (range, 18–55 years). Patients with ON had Ficat and Arlet Stage III, which is characterized by flattening out of the femoral head while the joint space is maintained (Fig. 1), whereas those with a femoral neck fracture had either a Garden [16] III or IV subcapital fracture

(complete fracture with partial or complete displacement of fracture fragments) (Fig. 2). In patients with ON, medical records indicated a well-maintained joint space, and Harris hip scores [20] (mean, 34.4; range, 24.7–54.0) indicated severe daily pain and failed response to nonoperative treatment. All patients were candidates for traditional hip arthroplasty. The minimum followup for patients with fracture was 6 months (mean, 23.3 months; range, 6–78 months); the minimum followup for patients with ON was 6 months (mean, 17.6 months; range, 6–41 months). Two patients in the fracture group and one patient in the ON group died before 2 years of followup, but no others were lost to followup. We had prior Institutional Review Board approval.

After patient consent, we performed unipolar hemiarthroplasty using a direct lateral approach [1]. Intraoperative observation revealed grossly intact acetabular cartilage. In unipolar hemiarthroplasty, the femoral head component articulates directly with the acetabular cartilage [45]. Each patient received either a press-fit or cemented, proximally porous-coated, titanium alloy Intermedics APR[®] II stem (Intermedics Orthopaedics, Inc, Austin, TX) with a modular pyrolytic carbon-coated head. Patients with poor bone stock, Dorr Type [13] C, were implanted with a cemented stem, whereas those with normal bone stock, Dorr Types A and B, received a press-fit stem. The Dorr bone classification describes the variation in femoral anatomy with Type A bone having a narrow canal and thick cortical walls and Type C bone having a wide canal and thin cortical walls. Type B bone is between Types A and C with a moderate canal with moderate cortical walls. The experimental component provided by the manufacturer was fabricated by depositing a 0.5-mm thick LTI pyrolytic carbon layer, at 1200°C, onto a graphite substrate preformed into a modular femoral head component [26]. The pyrolytic carbon contained a silicon alloy and had a surface porosity of 5 to 10 μm . The elastic modulus of pyrolytic carbon (13.7 GPa) [7] was similar to human cortical bone (13.7 GPa) but much lower than certain prosthesis materials (eg, 186-GPa zirconia) [41]. The graphite substrate had an elastic modulus of 11 GPa and compression strength of 137.9 MPa. Together, the graphite substrate and pyrolytic carbon coating produced promising mechanical properties (wettability, brittleness, and hardness) for use in hemiarthroplasty.

Postoperative rehabilitation was performed according to a standardized protocol, which used home health physiotherapy including a walker, limited weightbearing up to 20 pounds for the first 6 weeks, and progressed as tolerated thereafter. Patients were followed up at 3 months, 6 months, 1 year, and annually thereafter. Radiographs were taken (anteroposterior, frog leg lateral, and crosstable lateral) at each interval. Postoperative radiographs were evaluated by one of the authors (TLB) to rule out component loosening by

Fig. 1A–C (A) A preoperative anteroposterior radiograph of a 38-year-old man with Ficat and Arlet Stage III ON of the right hip shows femoral head collapse with a normal acetabulum and minimal cartilage wear. (B) An anteroposterior radiograph taken 1 day posthemiarthroplasty with a pyrolytic carbon endoprosthesis shows appropriate joint space and implant positioning. (C) Twenty-six months after surgery, minimal joint space narrowing was seen; however, clinically the patient had severe groin pain. He had successful conversion to a THA 3 weeks later.

Fig. 2A–B (A) A preoperative anteroposterior radiograph of a 69-year-old woman shows a femoral neck fracture with well-maintained joint space and minimal cartilage wear. (B) Fifty-one months after hemiarthroplasty with a pyrolytic carbon endoprosthesis, joint space and component positioning are well maintained.

assessment for radiolucency around fixation surfaces, progressive radiolucencies, pedestal formation, implant migration, or joint space narrowing. In patients who underwent revision surgery, direct assessment of femoral component stability was performed at the time of the operation by the surgeon.

Results

One patient (10%) in the fracture group underwent conversion to THA 6.5 years postoperatively as a result of severe pain and arthritic progression. Five of the seven patients with ON (71.4%) underwent conversion to THA at a mean of 22.2 months postoperatively (range, 6–51 months), owing to severe groin and gluteal pain (Table 1). At revision surgery, all five patients had accelerated acetabular wear as assessed by direct observation.

Of the two remaining patients, one died 10 months postoperatively secondary to renal failure and was unavailable for long-term followup. This patient had ON develop as a result of renal transplantation, and the implant material had no indication or relevance to his death. The other patient had conversion to THA 55 months posthemiarthroplasty owing to arthritis progression with protrusion. In this patient, the stem was retained, but the head was exchanged to match the acetabular cup. Gross inspection of the retrieved modular heads revealed no evidence of surface disruption, delamination, or third-body particles. Operative findings were most consistent with arthritis progression as evidenced by cartilage thinning and eburnation in all cases. All femoral components but one were stable and retained at the time of revision surgery. Revision or conversion to THA was performed to treat the pain and acetabular wear seen in the patients with failed prostheses. Severe groin and gluteal pain was the primary reason for revision.

Table 1. Patient data summary

Patient number	Age (years)	Gender	Preoperative diagnosis	Side	Press fit/cement	Failed?	End point (months)	Intraoperative findings: revision surgery
1	76	F	Fracture	R	Cement	No	Died; implant retained (71)	N/A
2	79	F	Fracture	L	Cement	No	Died; implant retained (49)	N/A
3	69	F	Fracture	R	Cement	No	Implant retained at final followup (72)	N/A
4	81	F	Fracture	R	Cement	No	Died; implant retained (59)	N/A
5	75	F	Fracture	R	Cement	No	Died; implant retained (85)	N/A
6	68	F	Fracture	L	Cement	No	Died; implant retained (13*)	N/A
7	94	F	Fracture	R	Cement	No	Died; implant retained (44)	N/A
8	71	M	Fracture	L	Cement	No	Died; implant retained (6*)	N/A
9	38	M	ON	R	Press fit	Yes	Conversion to THA (26)	Acetabular wear
10	35	M	ON	L	Press fit	Yes	Conversion to THA (55)	Diminished joint space
11	80	M	Fracture	L	Cement	No	Died; implant retained (70)	N/A
12	28	M	ON	R	Press fit	No	Implant retained at final followup (10*)	N/A
13	44	M	ON	R	Press fit	Yes	Conversion to THA (16)	Acetabular cartilage eroded, eburnation
14	62	F	Fracture	L	Press fit	Yes	Conversion to THA (71)	Protrusion type deformity in acetabulum, loose femoral component
15	55	M	ON	R	Press fit	Yes	Conversion to THA (91)	Absent articular cartilage, eburnation
16	18	F	ON	R	Press fit	No	Implant retained at final followup (39)	N/A
17	28	M	ON	L	Press fit	Yes	Conversion to THA (6)	Degenerative changes in articular cartilage

* Patients died before 24-month followup; F = female; M = male; ON = osteonecrosis; R = right; L = left; N/A = not applicable.

Discussion

Hemiarthroplasty in young patients has the potential for eliminating bearing wear, but has the disadvantage of cartilage wear. LTI pyrolytic carbon, an inert biomaterial has been used extensively in various human devices and reportedly reduces cartilage wear in canine hemiarthroplasties. We therefore initiated a prospective study in humans in 1990 when it was released for human use as a hemiarthroplasty. However, we unexpectedly observed failures in some patients. In this study, we documented and reported the high failure rate observed in the subset of patients treated with an LTI pyrolytic carbon femoral head for ON.

The limitations of this study were the small sample size, lack of a control group for the type of implant, short-term followup, and difference in age between the two groups. Despite these limitations, we believe the information is important because of the high failure rate in patients with ON. The patients in the ON group were younger and possibly more active, presumably affecting articular wear. Another possible reason for the higher failure rate in our series of patients with ON, when compared with previous reports of hemiarthroplasty for ON, was the device in our study was unipolar, whereas bipolar hemiarthroplasties were reported in previous studies. Because of the high failure rate in the first 17 enrolled patients and the existence of an already successful treatment for fractures at our clinical site (THA with a metal alloy implant), no additional implantations were performed and the study was closed. We did not characterize the prehemiartroplasty acetabular cartilage histologically between the two groups; any differences between the two might have had an effect on the early failures.

Hemiarthroplasty using metal alloys is a highly successful treatment for femoral neck fractures [17, 19, 42]. The use of unipolar and bipolar hemiarthroplasties for durable treatment of femoral fracture is well documented [9, 33, 37, 48]. Compared with the treatment of fracture, however, treatment of ON with hemiarthroplasty has not produced consistent and effective results. Reported failure rates have ranged from 0% to 50% with high incidences of pain, cartilage wear, and femoral head migration being noted [1–5, 12, 21, 32, 39]. Our data support the use of hemiarthroplasty with a pyrolytic carbon-coated endoprosthesis for treatment of femoral neck fractures but not for ON.

In the current literature, hemiarthroplasty for treatment of ON has been limited to bipolar devices with few articles providing results of unipolar implants. Ito et al. [21] examined 48 hips (mean age, 37 years) with ON treated with either cemented or uncemented primary bipolar hemiarthroplasty at an average followup of 11.4 years. They reported a 42% radiographic failure rate, 25%

revision rate, and 42% occurrence of groin pain. Lee et al. [27] compared 40 cementless bipolar hemiarthroplasties and 31 THAs in patients diagnosed with Ficat and Arlet Stage III ON. Although there were no reported revisions (mean followup, 8 years), they observed patients with bipolar hemiarthroplasties had higher incidences of gluteal and groin pain and a higher rate of femoral head migration. Cabanela [4] reported patients with ON treated with bipolar prostheses had a higher incidence of complications and underwent more revision procedures in comparison to patients who had THAs. These high incidences of gluteal pain, groin pain, and revision observed in patients with ON also were seen in the patients with ON in our study but to a higher degree (71.4% groin pain, 85.7% revision rate) with a similar patient age (mean, 35.1 years).

Conversely, other authors have reported low failure rates and excellent pain relief when using hemiarthroplasty as a treatment for patients with ON. Grevitt and Spencer [18] noted only one failure in 22 patients (mean followup, 40 months) produced an average postoperative Harris hip score of 88 and all patients had pain improvement. Chan and Shih [5] performed bilateral THAs and hemiarthroplasties in 28 young patients with Ficat and Arlet Stage III ON (with Grade 0 or 1 cartilage). They reported the hemiarthroplasty side produced satisfactory results (Merle D'Aubigné and Postel [11] score 15 or greater) and no differences between the groups in terms of clinical result, thigh pain, groin pain, osteolysis, dislocation, or revision rate. Their study suggested hemiarthroplasty as a reasonable alternative to THA. Thus, it is controversial whether hemiarthroplasty or THA should be the preferred treatment for patients with ON. Although hemiarthroplasty has been associated with groin pain [4, 21, 26, 27, 44] and head migration [4, 21, 44], the treatment would be beneficial in young patients if acetabular wear could be substantially reduced. LTI pyrolytic carbon hemiarthroplasty showed substantially less wear than titanium or cobalt chromium-molybdenum alloys in a canine model [8]. This benefit was anticipated but not realized in our human hemiarthroplasty application.

Ceramics have been studied as prosthetic materials for more than 30 years and have emerged as promising materials for THA by providing smoother surfaces that reduce bearing surface wear [46]. Reducing this wear is of particular concern for younger, more active patients in whom arthroplasty is now performed more frequently. The material properties of LTI pyrolytic carbon appear to make it an ideal ceramic-like material for use in orthopaedic prostheses. Originally conceived to contain gas emissions in the 1970s, the material is extremely resistant to fatigue failure [36]. The modulus of elasticity (13.7 GPa), which is controlled by adjusting silicon content, is similar to that of cortical bone (13.7 GPa). Thus, it is theorized pyrolytic

carbon can minimize the deleterious effects of stress shielding seen for materials with elastic moduli greater than that of bone (ie, alumina, zirconium, titanium, cobalt-chromium, and stainless steel). In addition, LTI pyrolytic carbon has excellent biocompatibility, wettability, and good fixation with direct apposition to bone [36, 46].

Our pilot data suggest an endoprosthesis with a LTI pyrolytic carbon-coated femoral head can have outcomes comparable to published outcomes for treatment of femoral neck fractures but is not effective for patients with ON. The patients with ON had normal joint space according to medical records, which was indicative of normal acetabular cartilage thickness. However, because we did not perform cartilage biopsy at the time of revision, the disease state was unknown as a contributory factor.

Future application of pyrolytic carbon in hemiarthroplasty still may have promising potential as suggested by the results in our fracture group. Subsequent to this study, the manufacturing process changed in that silicon alloy has been removed from the pyrolytic carbon and thus increased the surface finish (improved wettability and wear resistance; decreased friction) of the biomaterial. Although low-modulus ceramic-like materials appear valuable for THA [34], pyrolytic carbon hemiarthroplasty for ON was not successful in this pilot study and its use for unipolar treatment in patients with ON is not recommended.

References

- Amstutz HC, Grigoris P, Safran MR, Grecula MJ, Campbell PA, Schmalzried TP. Precision-fit surface hemiarthroplasty for femoral head osteonecrosis: long-term results. *J Bone Joint Surg Br.* 1994;76:423–427.
- Beaule PE, Amstutz HC. Management of Ficat Stage III and IV osteonecrosis of the hip. *J Am Acad Orthop Surg.* 2004;12:96–105.
- Beckenbaugh RD, Tressler HA, Johnson EW Jr. Results after hemiarthroplasty of the hip using a cemented femoral prosthesis: a review of 109 cases with an average follow-up of 36 months. *Mayo Clin Proc.* 1977;52:349–353.
- Cabanela ME. Bipolar versus total hip arthroplasty for avascular necrosis of the femoral head: a comparison. *Clin Orthop Relat Res.* 1990;261:59–62.
- Chan YS, Shih CH. Bipolar versus total hip arthroplasty for hip osteonecrosis in the same patient. *Clin Orthop Relat Res.* 2000;379:169–177.
- Cook SD, Beckenbaugh RD, Redondo J, Popich LS, Klawitter JJ, Linscheid RL. Long-term follow-up of pyrolytic carbon metacarpophalangeal implants. *J Bone Joint Surg Am.* 1999;81:635–648.
- Cook SD, Klawitter JJ, Weinstein AM. The influence of implant elastic modulus on the stress distribution around LTI carbon and aluminum oxide dental implants. *J Biomed Mater Res.* 1981;15:879–887.
- Cook SD, Thomas KA, Kester MA. Wear characteristics of the canine acetabulum against different femoral prostheses. *J Bone Joint Surg Br.* 1989;71:189–197.
- Cornell CN, Levine D, O'Doherty J, Lyden J. Unipolar versus bipolar hemiarthroplasty for the treatment of femoral neck fractures in the elderly. *Clin Orthop Relat Res.* 1998;348:67–71.
- Cossey AJ, Goodwin MI. Failure of Austin Moore hemiarthroplasty: total hip replacement as a treatment strategy. *Injury.* 2002;33:19–21.
- D'Aubigne RM, Postel M. Functional results of hip arthroplasty with acrylic prosthesis. *J Bone Joint Surg Am.* 1954;36:451–475.
- Dalldorf PG, Banas MP, Hicks DG, Pellegrini VD Jr. Rate of degeneration of human acetabular cartilage after hemiarthroplasty. *J Bone Joint Surg Am.* 1995;77:877–882.
- Dorr LD, Faugere MC, Mackel AM, Gruen TA, Bognar B, Malluche HH. Structural and cellular assessment of bone quality of proximal femur. *Bone.* 1993;14:231–242.
- Ficat RP. Idiopathic bone necrosis of the femoral head: early diagnosis and treatment. *J Bone Joint Surg Br.* 1985;67:3–9.
- Ficat RP, Arlet J. *Ischemia and Necrosis of the Bone.* Baltimore, MD: Williams & Wilkins; 1980.
- Garden RS. The structure and function of the proximal end of the femur. *J Bone Joint Surg Am.* 1961;43:576.
- Goldhill VB, Lyden JP, Cornell CN, Bochner RM. Bipolar hemiarthroplasty for fracture of the femoral neck. *J Orthop Trauma.* 1991;5:318–324.
- Grevitt MP, Spencer JD. Avascular necrosis of the hip treated by hemiarthroplasty: results in renal transplant recipients. *J Arthroplasty.* 1995;10:205–211.
- Haidukewych GJ, Berry DJ. Hip arthroplasty for salvage of failed treatment of intertrochanteric hip fractures. *J Bone Joint Surg Am.* 2003;85:899–904.
- Harris WH. Traumatic arthritis of the hip after dislocation and acetabular fractures: treatment by mold arthroplasty: an end-result study using a new method of result evaluation. *J Bone Joint Surg Am.* 1969;51:737–755.
- Ito H, Matsuno T, Kaneda K. Bipolar hemiarthroplasty for osteonecrosis of the femoral head: a 7- to 18-year followup. *Clin Orthop Relat Res.* 2000;374:201–211.
- Johnston CE, Ripley LP, Bray CB, Shaffer LW, Strong TE, Henning GD, Pruner RA. Primary endoprosthetic replacement for acute femoral neck fractures: a review of 150 cases. *Clin Orthop Relat Res.* 1982;167:123–130.
- Kawalec JS, Hetherington VJ, Melillo TC, Corbin N. Evaluation of fibrocartilage regeneration and bone response at full-thickness cartilage defects in articulation with pyrolytic carbon or cobalt-chromium alloy hemiarthroplasties. *J Biomed Mater Res.* 1998;41:534–540.
- Kenzora JE. Treatment of idiopathic osteonecrosis: the current philosophy and rationale. *Orthop Clin North Am.* 1985;16:717–725.
- Krackow KA, Mont MA, Maar DC. Limited femoral endoprosthesis for avascular necrosis of the femoral head. *Orthop Rev.* 1993;22:457–463.
- Lachiewicz PF, Desman SM. The bipolar endoprosthesis in avascular necrosis of the femoral head. *J Arthroplasty.* 1988;3:131–138.
- Lee SB, Sugano N, Nakata K, Matsui M, Ohzono K. Comparison between bipolar hemiarthroplasty and THA for osteonecrosis of the femoral head. *Clin Orthop Relat Res.* 2004;424:161–165.
- Lieberman JR. Core decompression for osteonecrosis of the hip. *Clin Orthop Relat Res.* 2004;418:29–33.
- Maistrelli G, Sessa V, Fornasier VL. Response of the articular cartilage to weight-bearing: comparison of hemiarthroplasty with ceramic and cobalt-chromium head in dogs. *Ital J Orthop Traumatol.* 1991;17:387–393.
- Minihane KP, Turner TM, Urban RM, Williams JM, Thonar EJ, Sumner DR. Effect of hip hemiarthroplasty on articular cartilage and bone in a canine model. *Clin Orthop Relat Res.* 2005;437:157–163.
- Mont MA, Marulanda GA, Seyler TM, Plate JF, Delanois RE. Core decompression and nonvascularized bone grafting for the

- treatment of early stage osteonecrosis of the femoral head. *Instr Course Lect.* 2007;56:213–220.
32. Naidu SI, McQueen DH. Follow-up study on hemiarthroplasty of the hip. *South Med J.* 1979;72:795–797.
 33. Ong BC, Maurer SG, Aharonoff GB, Zuckerman JD, Koval KJ. Unipolar versus bipolar hemiarthroplasty: functional outcome after femoral neck fracture at a minimum of thirty-six months of follow-up. *J Orthop Trauma.* 2002;16:317–322.
 34. Oonishi H, Wakitani S, Murata N, Saito M, Imoto K, Kim S, Matsuura M. Clinical experience with ceramics in total hip replacement. *Clin Orthop Relat Res.* 2000;379:77–84.
 35. Ortiguera CJ, Pulliam IT, Cabanela ME. Total hip arthroplasty for osteonecrosis: matched-pair analysis of 188 hips with long-term follow-up. *J Arthroplasty.* 1999;14:21–28.
 36. Park JB, Lakes RS. *Biomaterials: An Introduction.* 2nd Ed. New York, NY: Plenum Publishers; 1979.
 37. Raia FJ, Chapman CB, Herrera MF, Schweppe MW, Michelsen CB, Rosenwasser MP. Unipolar or bipolar hemiarthroplasty for femoral neck fractures in the elderly? *Clin Orthop Relat Res.* 2003;414:259–265.
 38. Schulz M, Muller-Zimmermann A, Behrend M, Krimmer H. [Early results of proximal interphalangeal joint replacement with pyrolytic carbon prosthesis (ascension) in idiopathic and post-traumatic arthritis] [in German]. *Handchir Mikrochir Plast Chir.* 2005;37:26–34.
 39. Scott RD, Urse JS, Schmidt R, Bierbaum BE. Use of TARA hemiarthroplasty in advanced osteonecrosis. *J Arthroplasty.* 1987;2:225–232.
 40. Scully SP, Aaron RK, Urbaniak JR. Survival analysis of hips treated with core decompression or vascularized fibular grafting because of avascular necrosis. *J Bone Joint Surg Am.* 1998;80:1270–1275.
 41. Shackelford JF, Alexander W, eds. *CRC Materials Science and Engineering Handbook.* 3rd Ed. Boca Raton, FL: CRC Press; 2001.
 42. Sikorski JM, Barrington R. Internal fixation versus hemiarthroplasty for the displaced subcapital fracture of the femur: a prospective randomised study. *J Bone Joint Surg Br.* 1981;63:357–361.
 43. Stutz N, Meier R, Krimmer H. Pyrocarbon prosthesis for finger interphalangeal joint replacement: experience after one year [in German]. *Unfallchirurg.* 2005;108:365–369.
 44. Takaoka K, Nishina T, Ohzono K, Saito M, Matsui M, Sugano N, Saito S, Kadowaki T, Ono K. Bipolar prosthetic replacement for the treatment of avascular necrosis of the femoral head. *Clin Orthop Relat Res.* 1992;277:121–127.
 45. Taljanovic MS, Jones MD, Hunter TB, Benjamin JB, Ruth JT, Brown AW, Sheppard JE. Joint arthroplasties and prostheses. *Radiographics.* 2003;23:1295–1314.
 46. Tian CL, Hetherington VJ, Reed S. A review of pyrolytic carbon: application in bone and joint surgery. *J Foot Ankle Surg.* 1993;32:490–498.
 47. Ushio K, Oka M, Hyon SH, Yura S, Toguchida J, Nakamura T. Partial hemiarthroplasty for the treatment of osteonecrosis of the femoral head: an experimental study in the dog. *J Bone Joint Surg Br.* 2003;85:922–930.
 48. Wolfson N, Waddell JP. Moore hemiarthroplasty functioning for 33 years: a case report. *Can J Surg.* 1995;38:542–544.
 49. Yun AG, Martin S, Zurakowski D, Scott R. Bipolar hemiarthroplasty in juvenile rheumatoid arthritis: long-term survivorship and outcomes. *J Arthroplasty.* 2002;17:978–986.
 50. Zilla P, Brink J, Human P, Bezuidenhout D. Prosthetic heart valves: catering for the few. *Biomaterials.* 2008;29:385–406.