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SHOULDER ARTHROPLASTY (G ATHWAL, SECTION EDITOR)

Porous metals and alternate bearing surfaces in shoulder arthroplasty

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Abstract Total shoulder arthroplasty (TSA) provides an effective solution for the treatment of glenohumeral arthritis. However, long-term outcomes have been limited by glenoid component aseptic loosening and polyethylene (PE) wear. Previous attempts to improve glenoid fixation with metal-backed glenoids resulted in inferior results. Newer component designs that contain porous metal allow for biological ingrowth of the prosthesis, potentially improving longevity and overall outcomes. Porous metal can also improve humeral component fixation, obviating the need for cement and simplifying revision surgery. Advances such as highly cross-linked polyethylene (HXLPE), vitamin E-doped HXLPE, and alternate bearing surfaces like ceramics and pyrolytic carbon have proven to provide superior wear characteristics in other joint replacements and may prove beneficial in the shoulder as well.

Keywords Total shoulder arthroplasty · Glenoid component failure · Porous metal · Trabecular metal · Stemless arthroplasty · Pyrolytic carbon

Introduction

Neer first developed a contemporary prosthesis for shoulder osteoarthritis in 1974 [1], and since then, shoulder arthroplasty has proven to be an effective method to decrease pain and improve patient function [2•, 3, 4]. The number of shoulder arthroplasties performed from 1993 to 2007 increased by 319 %, with a projected estimated increase of 10.6 % annually [5]. However, despite success and increased usage, total shoulder arthroplasty (TSA) is not without complications that result in failure and the need for revision surgery [6–10].

One of the most common causes of failure in total shoulder arthroplasty is glenoid loosening, which accounts for 24 % of all TSA complications [10–12]. The etiology of glenoid loosening is thought to be multifactorial and may be partially attributable to the implant's design [9, 13, 14••]. Since Neer's original glenoid design of a cemented all-polyethylene keeled component with conforming humeral and glenoid radii of curvature [15], the glenoid component has undergone many modifications. One of which, the metal-backed glenoid, came about due to concerns about glenoid loosening at the bone cement interface.

The metal-backed glenoid that was originally popularized by Cofield incorporated a metal backing with screw fixation and an exchangeable polyethylene liner [16]. The potential benefits of a metal-backed design were the opportunity for isolated polyethyelene exchange in a revision setting [17], improved cementless "biologic" fixation, and improved stress transfer between the implant and the bone [18]. Unfortunately, despite many variations to the design, metal-backed glenoids with polyethylene inserts have been found to be nonviable in the long-term due to increased levels of backside polyethylene wear, metalosis, osteolysis, loosening, and subsequent failure [19, 20••, 21•, 22, 23].

Due to the high risk of backside wear and failure of the metal-backed glenoids, the next iteration in glenoid component design reverted to an all-polyethylene component where the keel was exchanged for several pegs. The pegs were thought to lessen glenoid loosening due to their ability to

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individually resist shear forces at the bone-cement-implant interface [24]. Many studies found improved loosening performance of cemented pegged versus keeled all-polyethylene glenoids [25–28].

The next generation of all-polyethylene pegged glenoid components involved a central larger peg that possessed some sort of bone capture or bone ingrowth capability [29–31]. These implants have shown improved bony fixation and pull-out strength in early studies [31].

Porous metals

Porous metals are metals used in prostheses that have different size and number of holes in them to allow for interaction with the periprosthetic bone. They provide a truly biologic method of prosthesis implantation in which the metal surface is conducive to ingrowth of the bone into the porous channels. This living interface is thought to retain remodeling potential, allowing for the theoretical increased duration of fixation over cemented implants. Studies have shown that the ideal condition for bony ingrowth in porous metals is a pore size from 100 to 400 μm [32–34] with an optimal porosity of at least 50 % [35] (Table 1).

Porous metal use in the glenoid component

Despite the failure of the earlier metal-backed glenoid components, the desire for a cementless, tissue ingrowth capable glenoid component led to the development of a soft-metal-backed glenoid, the Sulmesh (Zimmer, Winterthur, Switzerland). These components had layers of titanium mesh welded together to form four porous pegs covering the backside of a polyethylene implant. Fucentese et al. [37] studied the 2-year follow-up of 22 patients using these implants and found a high failure rate of 13.6 %. They found that the implant failed at the metal peg and component body interface. Despite the unacceptably high failure rate, the implants that survived showed osteointegration appeared possible and signs of loosening were virtually nonexistent.

More recently, two companies have developed pegged glenoids that incorporate porous metal into their design. The first is the Zimmer "trabecular metal" (TM) glenoid. Its monoblock design is composed of a polyethylene glenoid face that is compression molded to a porous tantalum keel. The monoblock design is used to eliminate backside polyethylene wear seen with previous generations of metal-backed components. The keel is comprised of a five-peg cluster made of porous tantalum metal to promote stable bony ingrowth. To date, there is only one study in the literature that looks at the clinical and radiographic outcomes of this component. Budge et al. [38] prospectively evaluated their experience with 19 patients using the TM component. They found that all of the components except one had complete ingrowth of the porous tantalum keel; however, 21 % of the components had failed by fracture at the glenoid face-keel junction. The manufacturer has subsequently modified the design reported in their series, but no further studies have been undertaken to evaluate these changes.

The other pegged glenoid that incorporates porous metal is produced by Zimmer-Biomet (Zimmer-Biomet Orthopedics Inc., Warsaw, IN). It is a hybrid implant with four pegs and a modular central peg that can either be all polyethylene for fully cemented use, or exchanged for a porous titanium metallic central peg for bone ingrowth [16]. To date, there is no published data on the outcomes of this component.

Despite the paucity of literature, porous metal use in the glenoid component appears promising with regard to osteointegration and the potential for decreased glenoid loosening. However, due to the history of loosening and catastrophic failure seen in early iterations of these components, judicious use and close monitoring of these implants is currently recommended.

Table 1 Optimal characteristics for porous metals

Optimal pore size	100–400 μm
Optimal porosity	50 %
Limits of micromotion	150 μm

Source: [32–36]

Porous metal use in humeral components

There are many applications where the cementless bone ingrowth design of porous metals would be advantageous in the humeral component: from hemiarthroplasties used in proximal humerus fractures to stemless total shoulder arthroplasty designs.

Hemiarthroplasty

Hemiarthroplasty is a treatment option for many types of complex proximal humerus fractures that provides pain relief, but with variable functional outcomes [39–42].

Many studies report that proper positioning and healing of the greater tuberosity is a key for functional recovery after hemiarthroplasty for complex fractures [43–47].

In a retrospective analysis of 42 patients with a minimum of 2-year follow-up, Li and Jiang [48] showed satisfactory results and anatomic healing of the greater tuberosity in 93 % of the patients when a trabecular metal prosthesis was utilized.

Subsequently, a prospective study comparing the use of a conventional hemiarthroplasty to a trabecular metal-coated prosthesis in complex proximal humerus fractures was undertaken. This study revealed improved range of motion, better functional shoulder scores, and fewer radiographic

complications related to the greater tuberosity in the trabecular metal group compared to the conventional prosthesis [49].

Total shoulder arthroplasty

Although the most common complication is TSA is glenoid loosening [10–12], loosening of the humeral stem is also a potential long-term problem. Revision of a humeral stem because of infection, component malposition, or aseptic loosening can also be a challenge in a fully cemented stem due to stem extraction, complete cement removal, and potential bone loss [50]. An alternative is cementless fixation with biologic ingrowth provided by porous metal. First-generation ingrowth humeral stems had porous coating applied only under the humeral head with 9.7 % of stems judged at risk of loosening at an average of 4.6 years follow-up [51].

The next-generation prosthesis contained a circumferential porous coating around the proximal one fourth of the stem in an effort to improve humeral fixation. Retrospective analysis of two surgeons' experience with 76 patients using these stems revealed few radiolucencies and no loosening at an average of 52 months follow-up [52]. This study changed the surgeons' practice, and now, humeral stems are cemented only when a bony deficit is present.

A potential downside to cementless fixation previously seen in lower extremity arthroplasty is adaptive bone remodeling known as stress shielding [53, 54]. In the femur, stress shielding occurs when the bone shares its load-carrying capacity with a well-fixed cementless intramedullary implant. Consequently, the stress seen by the bone is reduced and this reduction causes bone resorption through adaptive remodeling [55–57].

One study sought to examine patterns of proximal humeral bone resorption after TSA with a cementless stem [58] and found a 17 % prevalence of full thickness cortical bone resorption in the proximal posterolateral humerus, predominantly in the first year after surgery. They found that the risk of bone resorption is significantly related to the ratio between the humeral shaft and prosthetic diameter, and that it increased with increasing stem size. Despite the bone loss, clinically, the patients were all asymptomatic, with no impairment in their shoulder function or need for revision surgery. It appeared that the bone loss was purely a radiographic finding, and no loosening was observed up to 5 years after surgery.

Reverse total shoulder arthroplasty

Unlike total shoulder arthroplasty, the rate of humeral loosening in reverse total shoulder arthroplasty (RTSA) is thought to be higher due to increased system constraint imparting a greater shear stress at the stem-bone interface [59, 60]. Uncemented humeral components may provide several advantages over cementation in RTSA such as a simplified operative technique, no systemic cement-related complications, a greater ease of revision, and long-lasting biologic fixation [61].

One study evaluated the clinical and radiographic outcomes of cementless RTSA [61] and found equivalent outcomes to cemented stems at a minimum 2-year follow-up. The cementless stems had a shorter operative time by 48 min. The literature shows that shorter operative times may be beneficial for decreasing infection rates [62–64]. There were radiographic findings of stress shielding in 5 of the 64 cementless stems; however, there were no signs of stems at risk for loosening. With a potential for decreased infection rates and improved simplicity of implant retrieval and bone preservation in a revision situation, the authors concluded that cementless fixation may very well provide several benefits over a cemented humeral stem [61].

Stemless prostheses

Stem-related complications in shoulder arthroplasty are well known including intraoperative humeral fracture, stress shielding, loosening, and traumatic periprosthetic fracture [6, 7, 10, 65–67, 68••, 69]. Stemless arthroplasty completely eliminates the humeral stem and relies entirely on metaphyseal fixation. This provides numerous potential benefits including the ability to perform implantation in malunited proximal humerus deformities, the elimination of periprosthetic humeral shaft fractures, and even greater bone preservation for revision situations [70].

Six manufacturers now offer a stemless prosthesis [71]. Three are undergoing investigational device exemption (IDE) clinical trials in the USA. As of March 2015, one device is currently approved by the FDA for use in the USA.

In 2004, the Biomet Total Evolutive Shoulder Systems (TESS) debuted in Europe as the first stemless device on the market. It is a three-component system based on a six-armed corolla metaphyseal component that is porous coated for improved bone fixation. There are currently four published reports regarding this prosthesis. Huguet et al. [72] reported the results of 63 Biomet TESS implants with a minimum follow-up of 3 years. They found no subsidence or loosening of the corolla, and no evidence of osteolysis, stress shielding, or radiolucent lines surrounding the corolla itself. In 2013, Razmjou et al. [73] performed a prospective longitudinal study comparing clinical and radiographic outcomes of three different prosthetic designs: the original Neer II system (Smith & Nephew, Memphis, TN, USA), Bigliani-Flatow (Zimmer), and the TESS. All three groups of patients had significant improvements in pain and function with high patient satisfaction. There were no lucent lines or stress shielding seen in the TESS group.

Also in 2013, Berth and Pap [74] conducted a prospective longitudinal study comparing TESS with the Mathys affinis (Mathys, Bettlach, Switzerland) stemmed system. Their

results with the TESS were comparable to the standard stemmed prosthesis, and no differences between the groups were identified.

The only device that is currently FDA approved for use in the USA is the Wright Medical-Tornier Simpliciti. This stemless device was first implanted in France in 2010 [70]. It is a two-piece system comprised of a humeral head implant and a metaphyseal component. The metaphyseal implant has a three-fin design, with bone ingrowth porous coating covering the majority of the three fins as well as the undersurface and the collar. There is currently no clinical data published for this implant.

Early studies of stemless implants show promise; however, data from the IDE clinical trials will be helpful in establishing whether these implants provide equal or superior clinical and radiographic outcomes compared to the current gold standard of stemmed shoulder arthroplasty.

Alternate bearing surfaces

The survivorship of total shoulder arthroplasty is 80–87 % at 15 years, limited primarily by the durability of the polyethylene glenoid component [66, 75, 76]. The glenoid component experiences higher stress and different modes of failure than hip and knee polyethylene due to increased eccentric loads, decreased bone stock, and poorer bone quality [9]. The cause of glenoid loosening is multifactorial, but glenoid component wear and subsequent generation of polyethylene debris and osteolysis is likely a major contributor [77].

It has been borne out in the hip and knee literature that modification of the polyethylene chemical structure or substitution of the metal on polyethylene bearing surfaces with alternate hard on hard bearing surfaces may produce dramatic decreases in component wear. The reduced rate of polyethylene wear in the shoulder compared to the hip and knee has limited the interest in alternative bearing surfaces in the shoulder; however, some are still being explored [78]. To date, there is very limited literature and research regarding the use of these alternate bearing surfaces in shoulder arthroplasty.

Polyethylene modifications

Metal on conventional ultrahigh-molecular-weight polyethylene (UHMWPE) has been the traditional bearing surface used in shoulder arthroplasty for many decades [79]. In hip arthroplasty, highly cross-linked UHMWPE (HXL-UHMWPE) has been used extensively and has shown to reduce wear rates by up to 90 % in vitro and in vivo [80–83].

In RTSA, osteolysis is thought to occur from scapular notching and polyethylene wear debris and is an important mode of failure [84]. The use of HXL-UHMWPE may decrease the rate of particle generation and wear-particle induced osteolysis, potentially improving implant survival and clinical outcomes in RTSA. However, highly cross-linking polyethylene can lead to a decrease in its mechanical properties (such as toughness, ductility, and resistance to fatigue) compared to conventional polyethylene [85–87].

Peers et al. [88] performed an in vitro wear study looking at the wear characteristics of HXL-UHMWPE in RTSA. They discovered an impressive 54 % reduction in the number of wear particles compared to conventional UHMWPE, potentially enhancing the clinical survival of RTSA. However, this reduction must be weighed against the decrease in dynamic mechanical properties such as fracture toughness and ultimate yield strength [89, 90]. Humeral liners often undergo rim loading and impingement that may leave the highly cross-linked polyethylene components susceptible to crack initiation, propagation, and ultimately failure [90].

One promising method to preserve the strength and fatigue properties of highly cross-linked polyethylene is to dope it with vitamin E [91, 92]. Doping polyethylene with vitamin E means impregnating it by soaking the molded UHMWPE in warm vitamin E, followed by prolonged diffusion at temperatures below the melting point of the polyethylene [92]. In one study, vitamin E doped polyethylene showed minimal changes in in vitro strength, fatigue-crack propagation resistance, and a 7–83 % reduction in wear compared to the control UHMWPE [92]. Subsequently, several in vitro studies have shown vitamin E stabilized UHMWPE has a higher oxidative stress resistance than standard UHMWPE, with equivalent wear rates and improved mechanical strength [91].

Ceramics

Alternate bearing surfaces such as metal-on-metal, ceramic-on ceramic, and ceramic-on poly have all been used in hip and knee arthroplasty with significantly lower wear rates that traditional hard on soft (metal on poly) surfaces. Ceramic bearing surfaces have been used in the hip for more than 20 years [77]. However, previous catastrophic femoral head failures have been reduced or eliminated with changes in materials and processing [93, 94]. Several problems provide a significant challenge for adapting the ceramic bearing surface to the shoulder: (1) the need for a thin glenoid component, (2) the desirability of a male taper on the head for glenoid exposure, and (3) the subsequent stress riser at the head-male taper junction [77]. Currently, the only shoulder prosthesis that utilizes a ceramic bearing surface is the Mathys affinis. This particular prosthesis has issued a hazard warning due to insufficient coupling and fracture at the coupling.

Pyrolytic carbon

Pyrolytic carbon (PyC) is another alternate bearing surface composed of a unique ceramic-like material with an excellent track record for durability and biocompatibility. It has been

used for over 40 years in heart valves. More recently, PyC has been utilized in small joint replacements in the upper extremity with mixed results [95–100]. PyC possesses a very low coefficient of friction and modulus of elasticity that is very similar to cortical bone [98]. There is great interest in using pyrolytic carbon for shoulder hemiarthroplasty because it has been shown to possibly regenerate cartilage and promote bone repair on the glenoid [96]. A recent study performed in Lyon, France, identified tissue that histologically resembled cartilage at the bone-PyC interface. The same group is currently undergoing animal studies to further understand the mechanism by which these tissues form [101].

Conclusions

Shoulder arthroplasty is a proven solution for many shoulder pathologies including arthritis, cuff tear arthropathy, and proximal humerus fracture. The longevity of shoulder prostheses may be limited by glenoid loosening and polyethylene wear. Porous metals may provide improved biological fixation in these devices leading to better longevity of the implants. More research is needed to determine the effect that porous metals, polyethylene modifications, and alternate bearing surfaces may have on the longevity and outcomes of shoulder arthroplasty.

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Compliance with ethical standards

Conflict of interest Shannon R. Carpenter, Ivan Urits, and Anand M. Murthi declare that they have no conflict of interest.

Human and animal rights and informed consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
- • Of importance
- •• Of major importance

1. Schrumpf M, Maak T, Hammoud S, Craig EV. The glenoid in total shoulder arthroplasty. Curr Rev Musculoskelet Med. 2011;4:191–9.
2.• Huff LR, Scalise JJ. The glenoid in total shoulder arthroplasty: current concepts. Curr Orthop Pract. 2013;24:393–6. **Good review of glenoid anatomy, pathoanatomy, and treatment options for the glenoid**.
3. Neer CS. Replacement arthroplasty for glenohumeral osteoarthritis. J Bone Joint Surg Am. 1974;56:1–13.
4. Norris TR, Iannotti JP. Functional outcome after shoulder arthroplasty for primary osteoarthritis: a multicenter study. J Shoulder Elb Surg. 2002;11:130–5.
5. Day JS, Lau E, Ong KL, Williams GR, Ramsey ML, Kurtz SM. Prevalence and projections of total shoulder and elbow arthroplasty in the United States to 2015. J Shoulder Elb Surg. 2010;19:1115–20.
6. Bohsali KI, Wirth MA, Rockwood Jr CA. Complications of total shoulder arthroplasty. J Bone Joint Surg Am. 2006;88:2279–92.
7. Chin PY, Sperling JW, Cofield RH, Schleck C. Complications of total shoulder arthroplasty: are they fewer or different? J Shoulder Elb Surg. 2006;15:19–22.
8. Fox TJ, Cil A, Sperling JW, Sanchez-Sotelo J, Schleck CD, Cofield RH. Survival of the glenoid component in shoulder arthroplasty. J Shoulder Elb Surg. 2009;18:859–63.
9. Matsen III FA, Clinton J, Lynch J, Bertelsen A, Richardson ML. Glenoid component failure in total shoulder arthroplasty. J Bone Joint Surg Am. 2008;90:885–96.
10. Wirth MA, Rockwood Jr CA. Complications of total shoulder-replacement arthroplasty. J Bone Joint Surg Am. 1996;78:603–16.
11. Cil A, Veillette CJ, Sanchez-Sotelo J, Sperling JW, Schleck CD, Cofield RH. Survivorship of the humeral component in shoulder arthroplasty. J Shoulder Elb Surg. 2010;19:143–50.
12. Gonzalez JF, Alami GB, Baque F, Walch G, Boileau P. Complications of unconstrained shoulder prostheses. J Shoulder Elb Surg. 2011;20:666–82.
13. Merolla G, Nastrucci G, Porcellini G. Shoulder arthroplasty in osteoarthritis: current concepts in biomechanics and surgical technique. Transl Med UniSa. 2013;6:16–28.
14.•• Pinkas D, Wiater B, Wiater JM. The glenoid component in anatomic shoulder arthroplasty. J Am Acad Orthop Surg. 2015;23:317–26. **A comprehensive review of glenoid anatomy, pathology, assessment, glenoid loosening, implantation techniques, and design**.
15. Williams GR, Abboud JA. Total shoulder arthroplasty: glenoid component design. J Shoulder Elb Surg. 2005;14:122S–8.
16. Churchill RS. Trends in glenoid component design in unconstrained shoulder arthroplasty. J Shoulder Elb Surg. 2011;20:S41–6.
17. Cheung EV, Sperling JW, Cofield RH. Polyethylene insert exchange for wear after total shoulder arthroplasty. J Shoulder Elb Surg. 2007;16:574–8.
18. Stone KD, Grabowski JJ, Cofield RH, Morrey BF, An KN. Stress analyses of glenoid components in total shoulder arthroplasty. J Shoulder Elb Surg. 1999;8:151–8.
19. Boileau P, Avidor C, Krishnan SG, Walch G, Kempf JF, Mole D. Cemented polyethylene versus uncemented metal-backed glenoid components in total shoulder arthroplasty: a prospective, double-blind, randomized study. J Shoulder Elb Surg. 2002;11:351–9.
20.•• Boileau P, Moineau G, Morin-Salvo N, et al. Metal-backed glenoid implant with polyethylene insert is not a viable long-term therapeutic option. J Shoulder Elb Surg. 2015;24:1534–43. **165 patients treated with metal-back, polyethylene glenoids over 5 years were followed clinically and radiographically for 12 years. A mean follow-up of 8.5 years showed a 46% survival rate. A total of 37% of patients required revision and 80% of those had polyethylene wear. Only 3% of patients could have isolated polyethylene exchange**.
21.• Papadonikolakis A, Matsen III FA. Metal-backed glenoid components have a higher rate of failure and fail by different modes in comparison with all-polyethylene components: a systematic review. J Bone Joint Surg Am. 2014;96:1041–7. **Systematic review of 21 studies on radiolucency, radiographic failure, and revision after arthroplasty with metal-backed glenoids (MBGs);**

23 studies with all polyethylene glenoids. They found the revision rate was 3 times higher for MBGs.
22. Tammachote N, Sperling JW, Vathana T, Cofield RH, Harmsen WS, Schleck CD. Long-term results of cemented metal-backed glenoid components for osteoarthritis of the shoulder. J Bone Joint Surg Am. 2009;91:160–6.
23. Taunton MJ, McIntosh AL, Sperling JW, Cofield RH. Total shoulder arthroplasty with a metal-backed, bone-ingrowth glenoid component. Medium to long-term results. J Bone Joint Surg Am. 2008;90:2180–8.
24. Giori NJ, Beaupre GS, Carter DR. The influence of fixation peg design on the shear stability of prosthetic implants. J Orthop Res. 1990;8:892–8.
25. Anglin C, Wyss UP, Nyffeler RW, Gerber C. Loosening performance of cemented glenoid prosthesis design pairs. Clin Biomech (Bristol, Avon). 2001;16:144–50.
26. Edwards TB, Labriola JE, Stanley RJ, O'Connor DP, Elkousy HA, Gartsman GM. Radiographic comparison of pegged and keeled glenoid components using modern cementing techniques: a prospective randomized study. J Shoulder Elb Surg. 2010;19:251–7.
27. Gartsman GM, Elkousy HA, Warnock KM, Edwards TB, O'Connor DP. Radiographic comparison of pegged and keeled glenoid components. J Shoulder Elb Surg. 2005;14:252–7.
28. Lazarus MD, Jensen KL, Southworth C, Matsen III FA. The radiographic evaluation of keeled and pegged glenoid component insertion. J Bone Joint Surg Am. 2002;84-A:1174–82.
29. Arnold RM, High RR, Grosshans KT, Walker CW, Fehringer EV. Bone presence between the central peg's radial fins of a partially cemented pegged all poly glenoid component suggest few radiolucencies. J Shoulder Elb Surg. 2011;20:315–21.
30. Churchill RS, Zellmer C, Zimmers HJ, Ruggero R. Clinical and radiographic analysis of a partially cemented glenoid implant: five-year minimum follow-up. J Shoulder Elb Surg. 2010;19:1091–7.
31. Wirth MA, Korvick DL, Basamania CJ, Toro F, Aufdemorte TB, Rockwood Jr CA. Radiologic, mechanical, and histologic evaluation of 2 glenoid prosthesis designs in a canine model. J Shoulder Elb Surg. 2001;10:140–8.
32. Berry DJ, Harmsen WS, Ilstrup D, Lewallen DG, Cabanela ME. Survivorship of uncemented proximally porous-coated femoral components. Clin Orthop Relat Res. 1995;319:168–77.
33. Cook SD, Thomas KA, Haddad Jr RJ. Histologic analysis of retrieved human porous-coated total joint components. Clin Orthop. 1988;234:90–101.
34. Spector M. Historical review of porous-coated implants. J Arthroplasty. 1987;2:163–77.
35. Berry DJ. Primary total hip arthoplasty. In: Chapman MW, editor. Chapman's orthopaedic surgery. Philadelphia: Lippincott Williams & Wilkins; 2001. p. 2769–90.
36. Callaghan JJ. The clinical results and basic science of total hip arthroplasty with porous-coated prostheses. J Bone Joint Surg Am. 1993;75:299–310.
37. Fucentese SF, Costouros JG, Kuhnel SP, Gerber C. Total shoulder arthroplasty with an uncemented soft-metal-backed glenoid component. J Shoulder Elb Surg. 2010;19:624–31.
38. Budge MD, Nolan EM, Heisey MH, Baker K, Wiater JM. Results of total shoulder arthroplasty with a monoblock porous tantalum glenoid component: a prospective minimum 2-year follow-up study. J Shoulder Elb Surg. 2013;22:535–41.
39. Bastian JD, Hertel R. Osteosynthesis and hemiarthroplasty of fractures of the proximal humerus: outcomes in a consecutive case series. J Shoulder Elb Surg. 2009;18:216–9.
40. Boileau P, Krishnan SG, Tinsi L, Walch G, Coste JS, Mole D. Tuberosity malposition and migration: reasons for poor outcomes after hemiarthroplasty for displaced fractures of the proximal humerus. J Shoulder Elb Surg. 2002;11:401–12.
41. Kontakis G, Koutras C, Tosounidis T, Giannoudis P. Early management of proximal humeral fractures with hemiarthroplasty: a systematic review. J Bone Joint Surg (Br). 2008;90:1407–13.
42. Krishnan SG, Bennion PW, Reineck JR, Burkhead WZ. Hemiarthroplasty for proximal humeral fracture: restoration of the Gothic arch. Orthop Clin N Am. 2008;39:441–50. **vi**.
43. Fialka C, Stampfl P, Arbes S, Reuter P, Oberleitner G, Vecsei V. Primary hemiarthroplasty in four-part fractures of the proximal humerus: randomized trial of two different implant systems. J Shoulder Elb Surg. 2008;17:210–5.
44. Gerber C, Hersche O, Berberat C. The clinical relevance of posttraumatic avascular necrosis of the humeral head. J Shoulder Elb Surg. 1998;7:586–90.
45. Huffman GR, Itamura JM, McGarry MH, et al. Neer award 2006: biomechanical assessment of inferior tuberosity placement during hemiarthroplasty for four-part proximal humeral fractures. J Shoulder Elb Surg. 2008;17:189–96.
46. Kralinger F, Schwaiger R, Wambacher M, et al. Outcome after primary hemiarthroplasty for fracture of the head of the humerus. A retrospective multicentre study of 167 patients. J Bone Joint Surg (Br). 2004;86:217–9.
47. Nijs S, Broos P. Outcome of shoulder hemiarthroplasty in acute proximal humeral fractures: a frustrating meta-analysis experience. Acta Orthop Belg. 2009;75:445–51.
48. Li F, Jiang C. Trabecular metal shoulder prosthesis in the treatment of complex proximal humeral fractures. Int Orthop. 2013;37:2259–64.
49. Li F, Zhu Y, Lu Y, Liu X, Wu G, Jiang C. Hemiarthroplasty for the treatment of complex proximal humeral fractures: does a trabecular metal prosthesis make a difference? A prospective, comparative study with a minimum 3-year follow-up. J Shoulder Elb Surg. 2014;23:1437–43.
50. Sanchez-Sotelo J, Wright TW, O'Driscoll SW, Cofield RH, Rowland CM. Radiographic assessment of uncemented humeral components in total shoulder arthroplasty. J Arthroplasty. 2001;16:180–7.
51. Sperling JW, Cofield RH, O'Driscoll SW, Torchia ME, Rowland CM. Radiographic assessment of ingrowth total shoulder arthroplasty. J Shoulder Elb Surg. 2000;9:507–13.
52. Throckmorton TW, Zarkadas PC, Sperling JW, Cofield RH. Radiographic stability of ingrowth humeral stems in total shoulder arthroplasty. Clin Orthop Relat Res. 2010;468:2122–8.
53. Bugbee WD, Culpepper WJ, Engh Jr CA, Engh Sr CA. Long-term clinical consequences of stress-shielding after total hip arthroplasty without cement. J Bone Joint Surg Am. 1997;79:1007–12.
54. Engh CA, Bobyn JD, Glassman AH. Porous-coated hip replacement. The factors governing bone ingrowth, stress shielding, and clinical results. J Bone Joint Surg (Br). 1987;69:45–55.
55. Engh Jr CA, Young AM, Engh Sr CA, Hopper Jr RH. Clinical consequences of stress shielding after porous-coated total hip arthroplasty. Clin Orthop Relat Res. 2003;417:157–63.
56. Huiskes R, Weinans H, van Rietbergen B. The relationship between stress shielding and bone resorption around total hip stems and the effects of flexible materials. Clin Orthop. 1992;274:124–34.
57. Huiskes R. The various stress patterns of press-fit, ingrown, and cemented femoral stems. Clin Orthop Relat Res. 1990;261:27–38.
58. Spormann C, Durchholz H, Audige L, et al. Patterns of proximal humeral bone resorption after total shoulder arthroplasty with an uncemented rectangular stem. J Shoulder Elb Surg. 2014;23:1028–35.
59. Favard L, Katz D, Colmar M, Benkalfate T, Thomazeau H, Emily S. Total shoulder arthroplasty - arthroplasty for glenohumeral arthropathies: results and complications after a minimum follow-up

of 8 years according to the type of arthroplasty and etiology. Orthop Traumatol Surg Res. 2012;98:S41–7.
60. Melis B, DeFranco M, Ladermann A, et al. An evaluation of the radiological changes around the Grammont reverse geometry shoulder arthroplasty after eight to 12 years. J Bone Joint Surg (Br). 2011;93:1240–6.
61. Wiater JM, Moravek Jr JE, Budge MD, Koueiter DM, Marcantonio D, Wiater BP. Clinical and radiographic results of cementless reverse total shoulder arthroplasty: a comparative study with 2 to 5 years of follow-up. J Shoulder Elb Surg. 2014;23:1208–14.
62. Colman M, Wright A, Gruen G, Siska P, Pape HC, Tarkin I. Prolonged operative time increases infection rate in tibial plateau fractures. Injury. 2013;44:249–52.
63. Willis-Owen CA, Konyves A, Martin DK. Factors affecting the incidence of infection in hip and knee replacement: an analysis of 5277 cases. J Bone Joint Surg (Br). 2010;92:1128–33.
64. Peersman G, Laskin R, Davis J, Peterson MG, Richart T. Prolonged operative time correlates with increased infection rate after total knee arthroplasty. HSS J. 2006;2:70–2.
65. Athwal GS, Sperling JW, Rispoli DM, Cofield RH. Periprosthetic humeral fractures during shoulder arthroplasty. J Bone Joint Surg Am. 2009;91:594–603.
66. Deshmukh AV, Koris M, Zurakowski D, Thornhill TS. Total shoulder arthroplasty: long-term survivorship, functional outcome, and quality of life. J Shoulder Elb Surg. 2005;14:471–9.
67. Farng E, Zingmond D, Krenek L, Soohoo NF. Factors predicting complication rates after primary shoulder arthroplasty. J Shoulder Elb Surg. 2011;20:557–63.
68.•• Kumar S, Sperling JW, Haidukewych GH, Cofield RH. Periprosthetic humeral fractures after shoulder arthroplasty. J Bone Joint Surg Am. 2004;86-A:680–9. **Review article discusses current status of stemless shoulder arthroplasty implants**.
69. Sperling JW, Cofield RH, Rowland CM. Minimum fifteen-year follow-up of Neer hemiarthroplasty and total shoulder arthroplasty in patients aged fifty years or younger. J Shoulder Elb Surg. 2004;13:604–13.
70. Churchill RS. Stemless shoulder arthroplasty: current status. J Shoulder Elb Surg. 2014;23:1409–14.
71. Petriccioli D, Bertone C, Marchi G. Stemless shoulder arthroplasty: a literature review. Joints. 2015;3:38–41.
72. Huguet D, Declercq G, Rio B, Teissier J, Zipoli B. Results of a new stemless shoulder prosthesis: radiologic proof of maintained fixation and stability after a minimum of three years' follow-up. J Shoulder Elb Surg. 2010;19:847–52.
73. Razmjou H, Holtby R, Christakis M, Axelrod T, Richards R. Impact of prosthetic design on clinical and radiologic outcomes of total shoulder arthroplasty: a prospective study. J Shoulder Elb Surg. 2013;22:206–14.
74. Berth A, Pap G. Stemless shoulder prosthesis versus conventional anatomic shoulder prosthesis in patients with osteoarthritis: a comparison of the functional outcome after a minimum of two years follow-up. J Orthop Traumatol. 2013;14:31–7.
75. Sperling JW, Cofield RH, Rowland CM. Neer hemiarthroplasty and Neer total shoulder arthroplasty in patients fifty years old or less. Long-term results. J Bone Joint Surg Am. 1998;80:464–73.
76. Torchia ME, Cofield RH, Settergren CR. Total shoulder arthroplasty with the Neer prosthesis: long-term results. J Shoulder Elb Surg. 1997;6:495–505.
77. Williams Jr GR, Iannotti JP. Alternative bearing surfaces–do we need them? Am J Orthop Belle Mead N J. 2007;36:15–7.
78. Jazrawi LM, Kummer FJ, DiCesare PE. Alternative bearing surfaces for total joint arthroplasty. J Am Acad Orthop Surg. 1998;6:198–203.
79. Goodman S. Bearing surfaces for joint replacement: new materials or new problems. In: Jones LC, Haggard WO, Greenwald AS (eds.) Metal-on-Metal Bearings. 2014:13–20.
80. Geerdink CH, Grimm B, Vencken W, Heyligers IC, Tonino AJ. Cross-linked compared with historical polyethylene in THA: an 8-year clinical study. Clin Orthop Relat Res. 2009;467:979–84.
81. Reynolds SE, Malkani AL, Ramakrishnan R, Yakkanti MR. Wear analysis of first-generation highly cross-linked polyethylene in primary total hip arthroplasty: an average 9-year follow-up. J Arthroplasty. 2012;27:1064–8.
82. Saikko V, Calonius O, Keranen J. Wear of conventional and cross-linked ultra-high-molecular-weight polyethylene acetabular cups against polished and roughened CoCr femoral heads in a biaxial hip simulator. J Biomed Mater Res. 2002;63:848–53.
83. Sato T, Nakashima Y, Akiyama M, et al. Wear resistant performance of highly cross-linked and annealed ultra-high molecular weight polyethylene against ceramic heads in total hip arthroplasty. J Orthop Res. 2012;30:2031–7.
84. Zumstein MA, Pinedo M, Old J, Boileau P. Problems, complications, reoperations, and revisions in reverse total shoulder arthroplasty: a systematic review. J Shoulder Elb Surg. 2011;20:146–57.
85. Atwood SA, Van Citters DW, Patten EW, Furmanski J, Ries MD, Pruitt LA. Tradeoffs amongst fatigue, wear, and oxidation resistance of cross-linked ultra-high molecular weight polyethylene. J Mech Behav Biomed Mater. 2011;4:1033–45.
86. Rimnac C, Pruitt L. How do material properties influence wear and fracture mechanisms? J Am Acad Orthop Surg. 2008;16 Suppl 1:S94–100.
87. Schroder DT, Kelly NH, Wright TM, Parks ML. Retrieved highly crosslinked UHMWPE acetabular liners have similar wear damage as conventional UHMWPE. Clin Orthop Relat Res. 2011;469:387–94.
88. Peers S, Moravek Jr JE, Budge MD, et al. Wear rates of highly cross-linked polyethylene humeral liners subjected to alternating cycles of glenohumeral flexion and abduction. J Shoulder Elb Surg. 2015;24:143–9.
89. Gomoll A, Wanich T, Bellare A. J-integral fracture toughness and tearing modulus measurement of radiation cross-linked UHMWPE. J Orthop Res. 2002;20:1152–6.
90. Nam D, Kepler CK, Nho SJ, Craig EV, Warren RF, Wright TM. Observations on retrieved humeral polyethylene components from reverse total shoulder arthroplasty. J Shoulder Elb Surg. 2010;19:1003–12.
91. Gigante A, Bottegoni C, Ragone V, Banci L. Effectiveness of vitamin-E-doped polyethylene in joint replacement: a literature review. J Funct Biomater. 2015;6:889–900.
92. Haider H, Weisenburger JN, Kurtz SM, et al. Does vitamin E-stabilized ultrahigh-molecular-weight polyethylene address concerns of cross-linked polyethylene in total knee arthroplasty? J Arthroplasty. 2012;27:461–9.
93. Cuckler JM, Bearcroft J, Asgian CM. Femoral head technologies to reduce polyethylene wear in total hip arthroplasty. Clin Orthop Relat Res 1995;57–63.
94. Fritsch EW, Gleitz M. Ceramic femoral head fractures in total hip arthroplasty. Clin Orthop Relat Res. 1996;129–136.
95. Chan K, Ayeni O, McKnight L, Ignacy TA, Farrokhyar F, Thoma A. Pyrocarbon versus silicone proximal interphalangeal joint arthroplasty: a systematic review. Plast Reconstr Surg. 2013;131:114–24.
96. Ricon FJ, Sanchez P, Lajara F, Galan A, Lozano JA, Guerado E. Result of a pyrocarbon prosthesis after comminuted and unreconstructable radial head fractures. J Shoulder Elb Surg. 2012;21:82–91.

97. Sarris IK, Kyrkos MJ, Galanis NN, Papavasiliou KA, Sayegh FE, Kapetanos GA. Radial head replacement with the MoPyC pyrocarbon prosthesis. J Shoulder Elb Surg. 2012;21:1222–8.
98. Sweets TM, Stern PJ. Pyrolytic carbon resurfacing arthroplasty for osteoarthritis of the proximal interphalangeal joint of the finger. J Bone Joint Surg Am. 2011;93:1417–25.
99. Van Nuffel M, Degreef I, Willems S, De Smet L. Proximal interphalangeal joint replacement: resurfacing pyrocarbon versus silicone arthroplasty. Acta Orthop Belg. 2014;80:190–5.
100. Wall LB, Stern PJ. Clinical and radiographic outcomes of metacarpophalangeal joint pyrolytic carbon arthroplasty for osteoarthritis. J Hand Surg Am. 2013;38:537–43.
101. Ouenzerfi G, Hassler M, Trunflo-Sfarghiu AM, Nallet A, Berthier Y. Triboligical behavior of pyrolytic carbon against bone promotes cartilage regeneration? http://leeds-lyon.sciencesconf.org/63177/document. Accessed 13 Nov 2015. Proceedings of the 42nd Leeds-Lyon Symposium on Tribology 2015.