The glenoid in shoulder arthroplasty

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Total shoulder arthroplasty is a common treatment for glenohumeral arthritis. One of the most common failure modes of total shoulder arthroplasty is glenoid loosening, causing postoperative pain, limitation of function, and potentially, the need for revision surgery. The literature has devoted considerable attention to the design of the glenoid component; efforts to better understand the biomechanics of the reconstructed glenohumeral joint and identify factors that contribute to glenoid component loosening are ongoing. This article reviews the current state of knowledge about the glenoid in total shoulder arthroplasty, summarizing the anatomic parameters of the intact glenoid, variations in component design and fixation, the mechanisms of glenoid loosening, the outcomes of revision surgery in the treatment of glenoid component failure, and alternative treatments for younger patients.
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Since the introduction of humeral head replacement in the 1950s as a treatment for complex proximal humeral fractures, and the subsequent addition of a glenoid resurfacing component, the indications for total shoulder arthroplasty (TSA) have expanded.[51,52,82] Currently, the most common shoulder pathology managed with TSA is glenohumeral osteoarthritis, accounting for approximately 20,000 cases annually in the United States.[61,82] For appropriately selected patients, TSA decreases pain and improves shoulder function.[34,54] In a recent meta-analysis of 23 clinical studies comparing TSA with humeral head replacement for treatment for primary glenohumeral osteoarthritis, Radnay et al[61] reported that TSA resulted in significantly better pain relief, postoperative range of motion, and patient satisfaction, with a lower revision rate compared with hemiarthroplasty.

Current indications for glenoid resurfacing include patients with painful glenohumeral incongruity, adequate glenoid bone stock, and an intact and functioning rotator cuff.[64] Typical pathologies that fit these indications include primary and secondary glenohumeral osteoarthritis and selected patients with inflammatory arthritis. Glenoid resurfacing is contra-indicated in patients with irreparable rotator cuff tears and inadequate glenoid bone stock. Active infection, neuropathic arthropathy, and paralysis of the periscapular musculature are contraindications for both hemiarthroplasty and TSA.[64]

Considerable attention has been devoted in the literature to the attributes of the glenoid component. To date, the

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most common middle-term and long-term complication of TSA is glenoid component loosening, causing post-operative pain, limitation of function, and potentially, the need for revision surgery.[76,82,83] Efforts to better understand the biomechanics of the reconstructed glenohumeral joint and identify factors that contribute to glenoid component loosening are ongoing.

This article reviews the current state of knowledge about the glenoid in TSA, summarizing the anatomic parameters of the intact glenoid, variations in component design and fixation, the mechanisms of glenoid loosening, the outcomes of revision surgery in the treatment of glenoid component failure, and alternative treatments for younger patients.

Glenoid anatomy

Anatomic parameters of the glenoid relevant to prosthesis design include glenoid height, width, articular surface area, inclination, vault size and shape, and version (Figure 1). An emphasis will be placed on glenoid version because this has been the focus of numerous recent studies. A number of cadaveric studies have demonstrated considerable natural variability in these parameters; this variability affects prosthesis design, instrumentation, and intraoperative implantation techniques. The reader is reminded, that care should be taken when interpreting and comparing data from multiple studies, because each uses different methodologies that are associated with their own inherent accuracy and precision.

Glenoid height is defined as the distance from the most superior and inferior points on the glenoid. In an evaluation of 412 cadaveric scapulae, Checroun et al[10] reported a mean glenoid height of 37.9 mm (range, 31.2-50.1 mm). In an evaluation of 140 shoulders of patients who were a mean age of 75 years, Iannotti et al[33] reported a mean glenoid height of 39 mm (range, 30-48 mm). In an evaluation of 5 shoulders from donors aged 66 to 84 years old, Sharkey et al[68] reported a mean glenoid height of 35.1 mm (range, 29.9-38.8 mm). In an evaluation of 12 cadaveric scapulae, Kwon et al[40] reported a mean glenoid height of 37.8 mm (range, 30-47 mm). Churchill et al[13] found a gender difference in specimens in an evaluation of 344 cadaveric scapulae, reporting a mean glenoid height of 37.5 mm (range, 30.4-42.6 mm) for men compared with 32.6 mm (range, 29.4-37 mm) for women. There was no difference in glenoid height between specimens from white and black patients. A smaller but similar gender difference in glenoid height was found by Mallon et al[43] in their evaluation of 28 cadaveric scapulae. They reported a mean glenoid height of 38 mm (range, 33-45 mm) for men compared with 36.2 mm (range, 32-43 mm) for women.

Glenoid width is defined as the distance from the most anterior and posterior points on the glenoid. Glenoid width is a function of the overall shape, which has been observed to be more pear-shaped than elliptical or oval. Checroun et al[10] reported that 71% of the 412 glenoids were pear-shaped; the remainder were elliptical. Pear-shaped glenoids have an upper width that is smaller than their lower width. Concerning this point, Iannotti et al[33] reported a mean upper glenoid width of 23 mm (range, 18-30 mm) and a mean lower glenoid width of 29 mm (range, 21-35 mm). Kwon et al[40] reported a mean glenoid width of 26.8 mm (range, 22-35 mm). Churchill et al[13] reported a difference in mean glenoid width of 27.8 mm (range, 24.3-32.5 mm) in male specimens compared with 23.6 mm (range, 19.7-26.3 mm) in female specimens. Once again, there was no difference in glenoid width between specimens from white and black patients. Mallon et al[43] reported a mean glenoid width of 28.3 mm (range, 24-32 mm) in male specimens compared with 23.6 mm (range, 17-27 mm) in female specimens.

As expected by the reported variability in glenoid height and width, glenoid articular surface area is reported with similar variation. In an evaluation of 32 cadaveric scapulae, Soslowsky et al[69] reported a mean articular surface area of 5.79 cm^2 in male specimens and 4.68 cm^2 in female specimens. Kwon et al[40] reported a mean articular surface area of 8.7 cm^2 (range, 7.0-14.2 cm^2).

Glenoid inclination is defined as the slope of the glenoid articular surface along the superior-inferior (SI) axis. Churchill et al[13] reported considerable variability in glenoid inclination. In male specimens, the glenoid was superiorly inclined by 4° (range, 7° inferior-15.8° superior inclination) compared with the glenoid being superiorly inclined by 4.5° in female specimens (range, 1.5° inferior-15.3° superior inclination). White patients tended to have slightly greater glenoid inclinations (mean, 4.6° superior inclination) than black patients (mean, 3.9° superior inclination).

Glenoid vault shape and size has been reported by Codsi et al.[15] They evaluated variations in glenoid vault shape and size from 3-dimensional (3D) computed tomography (CT) reconstructions of 61 cadaveric scapulae. By normalizing the measured glenoid vault geometry relative to the SI glenoid height, they were able to construct a normalized glenoid vault model. A review of this model revealed that the vault is approximately triangular for its entire length in the SI dimension. From this, Codsi et al proposed a family of 5 sizes of triangular implant prototypes that approximate the shape of each assessed scapula.

Glenoid version is defined as the angular orientation of the axis of the glenoid articular surface relative to the long (transverse) axis of the scapula; a posterior angle is denoted as retroversion. Numerous studies have assessed glenoid version in recent years; most cite a normal range varying from 2° anteversion to 9° retroversion and note changes in version in the presence of glenohumeral pathology.[13,26,57,62] Churchill et al[13] reported a mean glenoid retroversion of 1.2° (range, 9.5° anteversion-10.5° retroversion). Glenoids from men tended to be slightly more retroverted than those from women (mean, 1.5° compared with 0.9°, respectively) while those from white patients were significantly more retroverted than those from black (mean, 2.7° compared with 0.2°; $P < .00001$). Mallon et al[43] reported a mean glenoid retroversion of 6° (range, 2° anteversion-13° retroversion).
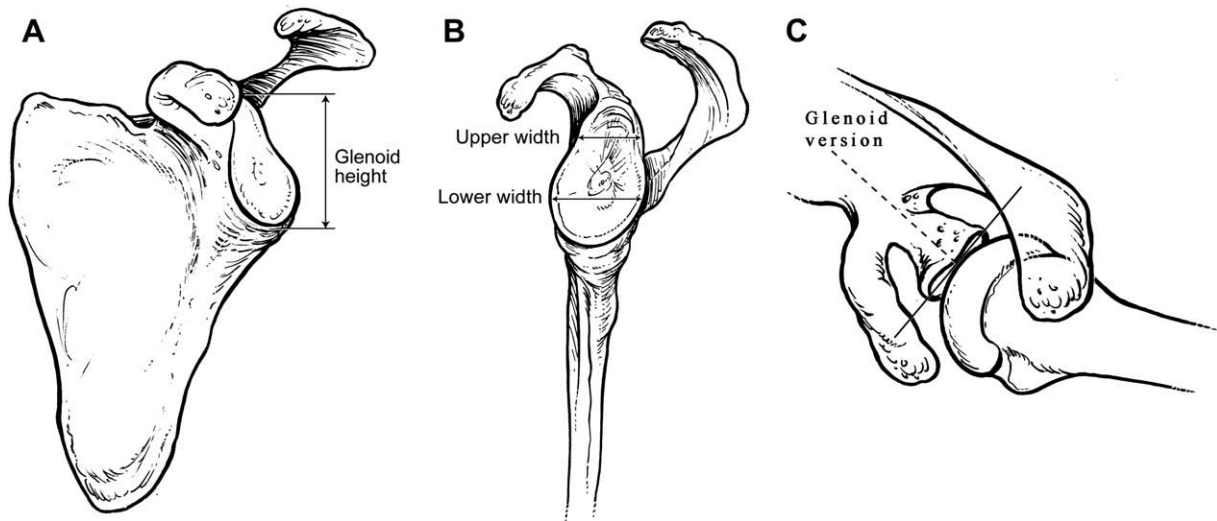
Figure 1 Parameters of glenoid anatomy include **(A)** glenoid height, **(B)** width, and **(C)** version. Considerable variation exists with respect to these parameters potentially affecting glenoid component design, instrumentation, and implantation techniques.

In a study of the relationship between glenoid version and glenoid pathology, Friedman et al[26] measured significant differences in glenoid version between 63 healthy controls vs 20 patients with glenohumeral arthritis by using data from CT scans of the shoulder. The healthy glenoids were oriented at a mean of 2° anteversion (range, 14° anteversion-12° retroversion), and those with glenohumeral arthritis were oriented at a mean of 11° retroversion (range, 2° anteversion-32° retroversion). Scalise et al[66] used 3D CT reconstructions to measure glenoid version in 14 individuals with unilateral glenohumeral osteoarthritis. The mean glenoid retroversion was 7° in the normal contralateral glenoid (range, 0°-14° retroversion) compared with a mean glenoid retroversion of 15.6° in the arthritic glenoid (range, 1° anteversion-33° retroversion).

Similarly, Couteau et al[20] used 3D CT reconstructions to measure glenoid version in 3 subsets of patients: those with early rotator cuff tears, those with primary osteoarthritis, and those with rheumatoid arthritis. In the early rotator cuff tear cohort, the mean glenoid retroversion was 8° (range, 2°-17° retroversion) compared with 16° in the osteoarthritis group (range, 0.2°-50° retroversion) and 15° in the rheumatoid arthritis group (range, 6°-22° retroversion).

Cyprien et al[22] conducted a radiographic study to compare the glenoid version of 50 healthy shoulders and 15 shoulders with chronic dislocation. They reported a significant difference in the glenoid retroversion of healthy (7.1° ± 4.6° left and 8.0° ± 5.0° right) and chronic dislocating (8.9° ± 5.6° left and 13.2° ± 4.0° right) shoulders.

Glenoid pathology

Glenoid involvement in degenerative arthritis varies with respect to the type of arthritic process affecting the glenohumeral joint.[17,45] Glenoid arthritis is frequently associated with glenoid wear. Walch et al[77] developed a classification system to describe glenoid wear patterns in the arthritic glenoid. For primary osteoarthritis, the most common pattern is posterior glenoid wear with varying degree of posterior subluxation of the humeral head.[17,45] Posterior glenoid wear in osteoarthritis is often accentuated clinically by the development of an internal rotation contracture as the condition progresses, further encouraging continued contact of the humeral head with the posterior aspect of the glenoid (Figure 2). Posteriorly worn glenoids are also associated with posterior instability.[19,48,51] As explained by Iannotti et al,[35] posteriorly worn glenoids have a decreased posterior wall height (less joint constraint) and cause the native joint reaction force to translate posteriorly, which creates an off-axis moment and a posteriorly directed shear force across the glenoid face.

Inflammatory arthritis is often associated with central glenoid erosion, which may be accompanied by the presence of cysts within the glenoid vault.[17] Anterior glenoid erosion can also be encountered. Uncommonly, the glenoid may be dysplastic in nature, altering the normal articulation with the humeral head. Evaluation of a dysplastic glenoid often demonstrates bony deficiencies posteriorly and inferiorly with posteroinferior subluxation of the humeral head.[17]

The extent and location of glenoid wear should be assessed preoperatively with axillary radiographs, axial CT scans through the glenohumeral joint, or 3D CT reconstructions. Scalise et al[65] measured glenoid retroversion and posterior bone loss in 24 shoulders using CT scans and 3D CT reconstructions. Using 2D CT scans, they reported a mean glenoid retroversion of 17° ± 2.2° and a posterior bone loss of 9 ± 2.3 mm. Using 3D CT reconstructions, they reported a mean glenoid retroversion of 19° ± 2.4° and a posterior bone loss of 7 ± 2 mm. Although agreement between the 4 recorders was very high using both 2D scans
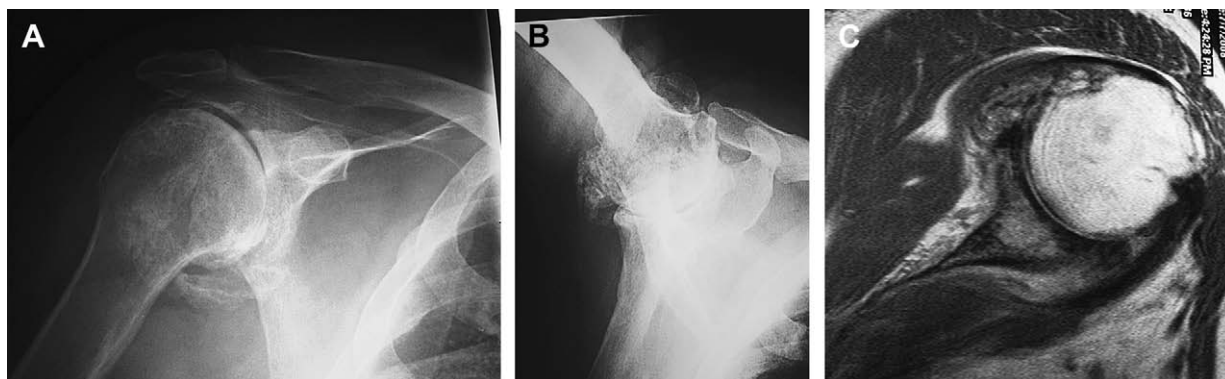
Figure 2 Glenoid involvement in degenerative arthritis varies according to the type of arthritic process present. Glenoid wear in osteoarthritis is typically posterior as seen in the (A) anteroposterior, (B) axillary views, and (C) axial computed tomography cuts.

and 3D reconstructions to measure glenoid version and posterior bone loss, Scalise et al concluded that surgical decision making was improved with the use of 3D data.

Nonconcentric glenoid wear is generally treated by eccentrically reaming the glenoid or bone grafting to correct glenoid version and improve fixation, though augmented glenoid designs have also been proposed.[63] Gillespie et al[28] conducted a cadaveric analysis of 8 specimens to evaluate the degree of glenoid retroversion that can be corrected with eccentric reaming. They reported that 10° of anterior correction resulted in a significant decrease in glenoid width, 15° of anterior correction resulted in an inability to seat the glenoid in 50% of the tested specimens due to inadequate bone stock, and 20° of anterior correction resulted in an inability to seat the glenoid in 75% of the tested specimens. These results led Gillespie et al to recommend that 10° of anterior correction may be the limit of correction, beyond that, consideration should be given to bone grafting.

Glenoid design and fixation in shoulder arthroplasty

Achieving long-term fixation of the glenoid is a primary goal in TSA. The low strength and small volume of available bone in the glenoid vault are limiting factors to securing fixation.[18,58] Several methods of fixation have been attempted, including cemented, noncemented, and hybrid or minimally cemented devices.

Cemented pegged and keeled components are used most commonly and are thought to provide the most predictable fixation (Figure 3). Noncemented glenoids rely upon mechanical interlock and biologic integration, typically by screw fixation or a combination of screw or press-fit pegs, or both, to achieve an initial fixation that facilitates long-term bone in-growth/on-growth (Figure 4). Although noncemented glenoids offer many theoretic advantages over cemented glenoids, noncemented glenoids have historically been associated
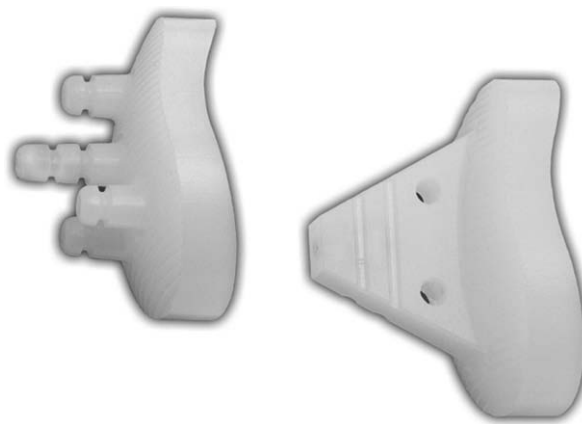

Figure 3 Cemented keeled and pegged glenoid designs for total shoulder arthroplasty.

with a higher complication rates due to increased ultra-high-molecular-weight polyethylene (UHMWPE) wear and issues to joint overstuffing.[7]

Hybrid fixation is a combination of the 2 techniques. Recent trends in the marketplace are to these more minimally cemented glenoid designs. These prostheses generally avoid the joint overstuffing pitfalls of noncemented designs by maintaining the overall thickness of conventional all-poly cemented glenoids (ie, they do not use a metal back) and achieve fixation through the use of press-fit modular metal pegs, sleeves, or other features that provide initial fixation without the use of cement. Minimally cemented prostheses are attractive because they require less removal of bone and use less cement.

Churchill et al[12] evaluated the effect of cement volume on glenoid bone temperature by measuring the temperature in the surrounding bone of 17 cadaveric shoulders. They found that the amount of bone at risk increased with cement volume used, concluding that dangerous amounts of heat are generated during cement polymerization and increased cement volume may make glenoid bone susceptible to thermal-induced bone necrosis, which could lead to glenoid loosening.
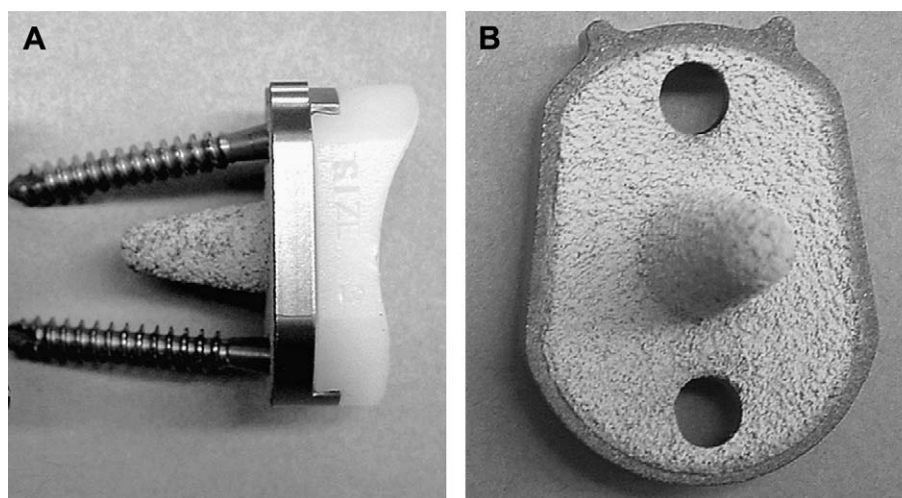
Figure 4 Example of a noncemented glenoid design where **(A)** initial fixation is achieved with 2 peripheral screws and **(B)** the component is press-fit into position using a central peg. (Adapted with permission from Rosenberg et al. Improvements in survival of the uncemented Nottingham Total Shoulder prosthesis: a prospective comparative study. BMC Musculoskelet Disor 2007;8:76.)

Considerable attention has been devoted to optimizing glenoid fixation. Efforts have been made to identify the optimal locations of fixation, the optimal types of fixation (including the influence of various design parameters on fixation), and the effect of glenoid deformity and shoulder pathology on achieving fixation. Considerable attention has also been devoted to identifying and understanding the glenoid failure modes and quantifying the survivorship of these devices.

Pegged vs keeled cemented components

Lazarus et al[41] reviewed the initial and postoperative radiographs of 328 patients who underwent TSA in which 39 received keeled glenoids and 289 received pegged glenoids. They evaluated seating of the glenoid component and the presence of radiolucent lines around the prosthesis. Compared with the keeled design, pegged glenoid components had significantly better seating and fewer radiolucencies. Lazarus et al concluded from results that a superior technical outcome, in the form of better implant seating was achieved with pegged glenoids.

In a prospective randomized radiographic comparison of pegged and keeled glenoids, Gartsman et al[27] reported that at 6 weeks after surgery, 39% of keeled components and only 5% of pegged glenoids had radiolucent lines. They graded the extent of radiolucency on a 5-point scale (0 meaning no radiolucencies) and reported a mean score of 1.4 for the keeled and 0.5 for pegged glenoids. Nuttall et al[55] conducted a radiostereometric analysis of 20 TSA patients comparing the micromotion associated with keeled and pegged glenoids. During a 2-year follow-up, they observed that keeled glenoids were associated with significantly more translation and rotation than pegged glenoids. Nuttall et al hypothesized

that the increased translation and rotation of the keeled glenoids were due to the greater amount of cement required for fixation, adding that the exothermic properties of cement can potentially induce bone necrosis.

Keel design

Murphy et al[49] performed a finite element analysis (FEA) comparing 2 keeled glenoid designs, one with a centrally located keel and another with an anteriorly offset keel. Under abduction and flexion loading conditions, the offset keel was subjected to lower bending stresses than the centrally located keel. They hypothesized that the anteriorly offset keel was associated with lower stress because it was more directly aligned with the applied force and because the anteriorly offset keel conserves a greater amount of the more dense bone, noting that posterior glenoid bone is more dense than the anterior bone that is removed during implantation. In a similar FEA, Orr et al[58] compared the stresses associated with 2 keeled glenoid designs, one with a centrally located keel and another with an inferiorly offset keel, during normal glenoid loading. Glenoids with an inferiorly offset keel more closely replicated the normal stresses of the glenoid compared with that of a centrally located keel.

Flat vs curved-backed cemented components

Szabo et al[72] reviewed the radiographic results of flat- and curved-back glenoids in 66 TSAs in 63 patients. Radiographs from the immediate postoperative period demonstrated that 65% of curved-back glenoids were perfectly seated (no radiolucent lines present) compared with only 26% of flat-back glenoids. At the 2-year follow-up, some

radiolucency was present in all of the implanted glenoids; however, the radiolucency scores of the flat-back glenoids were significantly worse.

Anglin et al[1] conducted a laboratory analysis comparing the resistance to loosening associated with flat- and curved-back glenoid designs when subjected to cyclic, eccentric loading. The curved-back glenoids were associated with nearly 50% less distraction than that of the flat-back glenoids. They hypothesized that these favorable results were attributable to curved-back glenoid designs preserving more bone during implantation (eg, reaming) and because they are associated with less shear stress; that is, curved-back glenoids convert some shear stresses to compressive stresses.

Iannotti et al[35] conducted a FEA to assess the effect of implant malposition on flat- and curved-back glenoids. Malposition was assessed by testing the 2 implants in 0° and 20° retroversion. The peak strains measured in the flat-back glenoid were greater than those of the curved-back glenoid; the peak strains associated with each implant increased in the retroverted condition. The amount of lift-off and slip associated with the flat-back glenoid was significantly greater than that of the curved-back glenoid. These results led Iannotti et al to conclude that curved-back glenoids are less susceptible to malpositioning-related failure modes.

Cement fixation

Several studies have assessed the effect of cement mantle thickness and cement preparation techniques on cement fixation and the incidence of radiolucent lines. Terrier et al[75] used FEA to assess the stresses in the bone and cement under concentric and eccentric loading and in a bonded and debonded condition. Each situation was assessed at uniform cement mantle thicknesses of 0.5, 1, 1.5, and 2 mm with a flat-backed keeled glenoid. Increases in cement mantle thickness caused a decrease in the observed cement stress; whereas, the observed bone stress was minimized for cement mantle thicknesses between 1 and 1.5 mm. Eccentric loading and the debonded condition increased the overall observed stress in the bone and cement; peak stresses were observed at the posterior side/end of the keel in each condition. From these results, Terrier et al concluded that a uniform cement mantle thickness of 1.0 mm is ideal.

Nyffeler et al[56] conducted an axial pullout test to assess the effect of cement mantle thickness (0.1 vs 0.6 mm) and surface finish (smooth vs rough) on the fixation of cylindrical, notched, and threaded peg designs. Threaded pegs had a significantly higher pullout force than notched pegs, and notched pegs had a significantly higher pullout force than cylindrical pegs. A rougher surface finish resulted in a significantly higher pullout force for the cylindrical and notched pegs, but not the threaded pegs. Increasing cement mantle thickness from 0.1 to 0.6 mm resulted in a significantly higher pullout force for all designs, and a cement mantle thickness of 0.1 mm resulted in an incomplete (nonuniform) thickness around each peg.

The previously mentioned study by Anglin et al[1] also assessed the relationship between surface finish and cement fixation by comparing the resistance to loosening associated with smooth- and roughened-back glenoids. Roughened-back glenoids remained stable after 250,000 eccentric loading cycles, but the smooth-back glenoids debonded from the cement during the first loading cycle.

Regarding the effect of cement preparation on fixation (as determined by the presence of radiolucent lines), Barwood et al[6] conducted an initial postoperative radiographic study of 69 patients with a cemented pegged glenoid. In each case, a cement pressurization instrument was used 4 times to improve cement interdigitation into cancellous bone. No visible radiolucencies were found on the initial postoperative radiograph of 60 of 69 shoulders (90%); on a scale of 0 to 5 (0 being no radiolucencies), the average radiolucency score was 0.14. They concluded that a low incidence of early radiolucencies can be achieved by cement pressurization when used in conjunction with glenoid reaming and size matching of the glenoid. A reduction in radiolucencies using pressurization techniques was reported by Klepps et al.[38]

Cemented vs noncemented glenoids

Boileau et al[7] conducted a prospective randomized study of 40 shoulders in 39 patients (mean age, 69 years) in which they compared the postoperative outcomes of cemented and noncemented (metal-back) glenoids (Aequalis, Tornier Inc, Edna, MN). Although not significant, all average postoperative functional measures were better in the noncemented group at 1, 2, and 3 years of follow-up. In addition, the incidence of postoperative radiolucent lines was significantly lower after implantation of a noncemented glenoid (25% compared with 85% in the cemented group). However, the incidence of implant loosening requiring revision surgery was significantly higher for the noncemented group (20% vs 0%).

Boileau et al reported 2 causes of metal-back glenoid loosening: mechanical, from lack of initial stability; and biologic, from osteolysis caused by poly and metal wear debris. Adding, the 4 primary failure modes of metal-back glenoids are: (1) insufficient polyethylene thickness (4 instead of 5 mm); (2) excessive thickness of the component (7 mm) that over-tensions the rotator cuff; (3) rigidity of the metal-back component that accelerates polyethylene wear and stress-shields bone; and (4) posterior/eccentric loads on the glenoid that lead to polyethylene disassociation. For these reasons, Boileau et al concluded that the fixation of metal-back glenoids is inferior to that of cemented glenoids.

Wallace et al[79] conducted a retrospective analysis of 32 cemented glenoids and 26 noncemented glenoids for

a mean follow-up of 5 years. They reported no significant differences in postoperative pain, range of motion, or overall shoulder function; however, radiolucent lines and the proportion of implants classified as ''probably loose'' was higher in the group with cemented glenoids. Although 5 of the 8 revisions performed occurred in patients with noncemented glenoids, these revisions were performed for reasons other than loosening. In the early postoperative period, the poly disassociated from the metal tray in 2 glenoids, and 3 glenoids were revised for early instability. In addition, postoperative radiographs showed 3 of the noncemented, metal-backed glenoids had broken screws. Wallace et al concluded that the intermediate outcomes of noncemented glenoids are comparable with those of cemented glenoids despite a higher rate of early complications.

Several studies have conducted survivorship estimates of metal-backed glenoids. Martin et al[44] retrospectively evaluated 140 noncemented glenoids for a mean follow-up of 7.5 years and reported 16 implants (11.4%) failed clinically. These failures included 2 fractured glenoid metal-backed components, 9 polyethylene delaminations/disassociations, and 5 cases of aseptic loosening. In addition, 38% of these implants had evidence of radiolucent lines and 16 had broken screws (4 of which failed clinically). On the basis of these results, Martin et al predicted a 10-year survivorship of 85% with noncemented glenoid components. They also identified 3 factors that were significantly associated with clinical failure: male gender (3 times the failure rate of female patients), postoperative pain, and the presence of radiolucent lines on the back of the glenoid.

Taunton et al[74] retrospectively analyzed 83 TSAs with a metal-backed, noncemented glenoid (Cofield Shoulder, Smith & Nephew, Memphis, TN) for a mean follow-up of 9.5 years. There was radiographic evidence of glenoid loosening in 33 shoulders (40%) and significant poly-ethylene wear in 21 (25%); 26 shoulders required revision. Taunton et al predicted 5-year Kaplan-Meier survival esti-mates (free of revision) of 86.7% (79% free of radiographic failure) and a 10-year estimate of 78.5% (51.9% free of radiographic failure).

Tammachote et al[73] retrospectively analyzed 100 TSAs with a metal-backed, cemented glenoid (Neer II Shoulder, Smith & Nephew) for a mean follow-up of 10.8 years. They reported radiographic evidence of glenoid loosening in 69 shoulders (83%) at a minimum radiographic follow-up of 2 years; 5 shoulders required revision (2 for aseptic glenoid loosening and 1 for poly wear). From these results, Tam-machote et al predicted a survivorship of 97% at 5 years and 93% at 10 years.

Several FEA studies have evaluated the stresses in cemented and noncemented glenoids. Gupta et al[29] con-ducted a FEA on a metal-back glenoid using CT data at different physiologic loading conditions, with and without the use of cement. They documented high Von Mises stresses in the metal backing during shoulder range of motion, especially during abduction. In addition, they reported lower stresses in the glenoid bone under the metal backing, indicative of stress shielding. The stresses in the noncemented glenoid polyethylene were 20% less than that in the cemented glenoid polyethylene, suggesting that the noncemented glenoid may be less susceptible to glenoid wear.

An FEA by Stone et al[71] of cemented and noncemented glenoids found cemented, all-polyethylene glenoids had an overall stress pattern that more closely resembled the intact, native glenoid. The noncemented metal-back glenoid was associated with lower stresses in the subchondral glenoid bone, indicative of stress shielding. They also reported high stress regions at the poly-metal interface, particularly during eccentric loading of the noncemented glenoid. Stone et al concluded that noncemented glenoids were associated with increased polyethylene wear and had a greater potential for failure relative to cemented glenoids.

The reported incidence of broken screws and clinical failure of noncemented glenoids highlights the importance of achieving stable initial fixation, which is necessary to promote osseous integration of the implant. Recent studies have examined the quality and density of the bone within the glenoid vault in an effort to determine the optimal location for screw fixation. Codsi et al[16] used 3D CT reconstructions of 27 cadaveric scapulae to assess the ideal starting location, length, and angle of glenoid fixation screws. They reported 3 locations for screw placement: the first in a 5-mm area of the superior glenoid, a second in a 7-mm area in the middle of the glenoid, and a third in a 5-mm area in the inferior portion of the glenoid (Figure 5). With these 3 starting points, screws can be placed through the glenoid fossa into bone beyond the glenoid vault. Codsi et al reported that the median length of an optimally placed screw in the superior, middle, and inferior glenoid was 29, 60, and 75 mm, respectively.

Anglin et al[2] analyzed the mechanical properties of the cancellous bone of 10 cadaveric scapulae at different locations on the glenoid. The posterosuperior aspect of the glenoid had the strongest and stiffest cancellous bone, followed by the superior and anterior regions. Although the central portion of the glenoid had the weakest cancellous bone, this location had the greatest depth into the glenoid vault. They concluded that initial implant fixation should include deep fixation within the central portion of the gle-noid and be augmented by fixation in the stronger regions of the glenoid, located posterosuperiorly and anteriorly.

The issues related to wear and joint overstuffing may be remedied by the development of biomaterials that are thinner and more resistant to wear and fracture. Wirth et al[81] evaluated the wear properties associated with identical glenoids processed with different sterilization techniques, using a gas plasma and 50-kGy gamma irradiation. The cross-linked components sterilized with 50-kGy gamma irradiation were associated with an 85% reduction in gravimetric wear compared with the glenoids sterilized
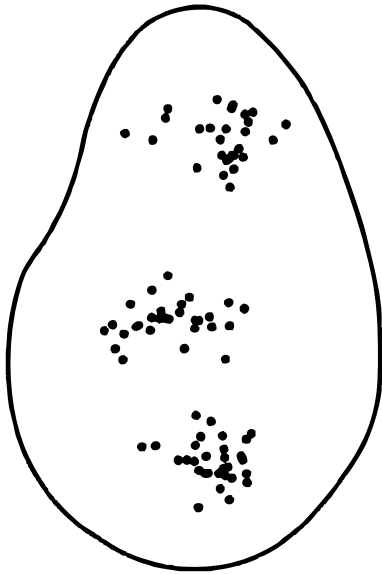
Figure 5   Ideal starting locations for screw fixation of non-cemented glenoid component designs. (Adapted with permission from Codsi et al. Locations for screw fixation beyond the glenoid vault for fixation of glenoid implants into the scapula: an anatomic study. J Shoulder Elbow Surgery 2007;16(3 suppl):S84-9.)

with gas plasma (7.0 ± 0.4 and 46.7 ± 2.6 mg/million cycles, respectively). From these results, Wirth et al concluded that though each material produced wear particles in the biologically active size range, the cross-linked glenoids would have a lower osteolytic potential due to the significantly lower wear rate.

Glenoid loosening

Glenoid loosening is associated with increased pain, decreased shoulder function, and the need for revision surgery[76,83] (Figure 6). The reported incidence of glenoid loosening varies considerably, from as low as 0% to 12.5%[64,82] to as high as 96%, assuming radiolucent lines are indicative of early loosening.[5,8,18,31,51] The mechanism of glenoid loosening is thought to be repetitive, eccentric loading of the humeral head on the glenoid, commonly called "the rocking horse" phenomenon. This eccentric or edge loading condition produces a torque on the fixation surface that induces a tensile stress at the bone-implant or bone-cement-implant interface, potentially causing interfacial failure and glenoid disassociation.

Normal glenohumeral motion includes rotation and translation of the humeral head. Karduna et al[36] reported that the humeral head translates 1.5 mm in the anteroposterior (AP) direction and 1.1 mm in the SI direction during active motion. McPherson et al[47] measured humeral head translation from radiographs and reported that the humeral head translates 4 mm in the AP direction during active motion. This physiologic motion results from the

bony incongruence of the glenoid and humerus and the corresponding congruency of the surrounding soft tissue, that is, the articular cartilage and the labrum. When the glenoid is resurfaced with a conforming articular surface, eccentric loading results due to the inadequacy of UHMWPE to mimic the viscoelastic properties of the articular cartilage and labrum.

Eccentric loading can occur in any direction, although SI eccentric loading is most common, presumably due to the propensity for humeral head migration with a weak or failing rotator cuff. Eccentric loading may also result from incomplete glenoid seating, glenoid malposition, or humeral malposition. Each of these conditions can cause the humeral head to not be centered on the glenoid articular surface when the shoulder is in the neutral position.

The magnitude and frequency of eccentric loading is more severe if the rotator cuff is weak or failing. The effect of eccentric loading is more significant if the implant fixation is suboptimal. Efforts to minimize these detrimental effects of eccentric loading focus on prosthetic articular conformity (radial mismatch) and proper implant positioning.

Radial mismatch

Recent studies have attempted to optimize prosthetic articular conformity to simulate native glenohumeral kinematics; doing so offers the potential of minimizing the detrimental effects of eccentric loading. Articular conformity, commonly known as "radial mismatch," is defined as the difference in curvature between the humeral head component and the glenoid.[78] More conforming designs have an increased level of constraint (ie, smaller radial mismatches) and are thought to limit humeral head translation during motion, invoking shear forces or edge loads that can damage fixation. Conversely, less conforming designs (ie, larger radial mismatches) allow greater humeral head translation but have a lower surface area; therefore, these designs are at risk for increased wear, polyethylene fracture, and joint stability may be a concern.[25,78] Regarding this point, we remind the reader that radial mismatch is a nonnormalized parameter; thus, a radial mismatch of 4 mm for a 38-mm humeral head is not functionally equivalent to a radial mismatch of 4 mm for a 53-mm humeral head. Normalization of articular conformity, and thus comparison, can be achieved by ratios of the mating articular curvature, a joint congruency ratio.

Several bench tests have analyzed the effect of varying joint conformity on restoring glenohumeral kinematics and stability. Karduna et al[36] evaluated the effect of varying radial mismatch from 0 to 5 mm on glenohumeral translation in 7 cadaveric shoulders before and after TSA.[36] Humeral head translation in the reconstructed shoulder was linearly related to radial mismatch, where a greater radial mismatch was associated with greater humeral head
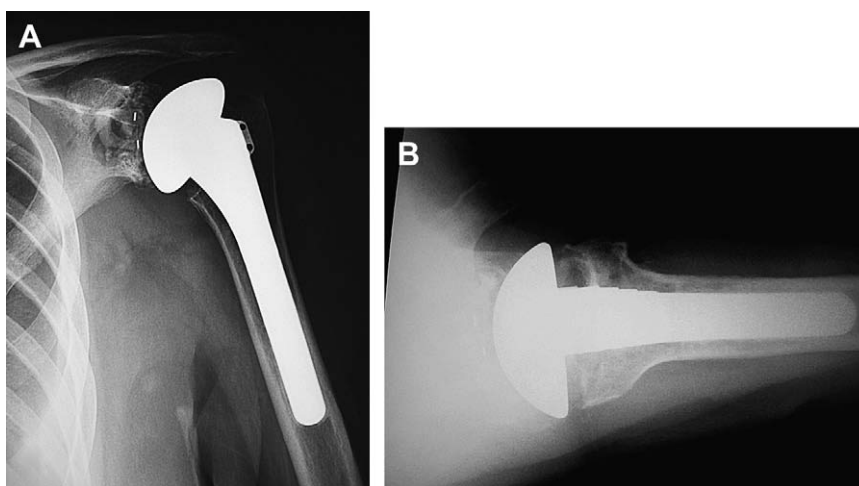
Figure 6 Patient with glenoid loosening that presented with increased pain and limited active shoulder range of motion. Note the radiolucent lines surrounding the glenoid component.

translation. From the results of this study, Karduna et al concluded that a radial mismatch of 4 mm best simulated the normal glenohumeral kinematics.

In a similar but separate study, Karduna et al[37] evaluated the effect of varying radial mismatch from 0 to 5 mm on glenohumeral stability in the anterior and posterior direction after TSA. By varying humeral head height for the same size glenoid component, they were able to eliminate the contribution of component constraint (ie, glenoid wall height) and isolate the contribution of joint conformity (ie, radial mismatch) on joint stability. As previously reported, anterior and posterior displacement increased with greater radial mismatch. Despite greater displacement before dislocation, the minimum force required for dislocation varied by an average of only 3%. Karduna et al concluded that varying radial mismatch from 0 to 5 mm results in a clinically insignificant change in joint stability.

Anglin et al[1] conducted a laboratory analysis of 6 different glenoid designs. They reported that subsequent to cyclic, eccentric loading, the nonconforming glenoid design (radial mismatch of 5 mm) had half the glenoid tensile displacement as the more conforming glenoid (radial mismatch of 1.77 mm).

The effect of joint conformity on clinical outcomes has also been reported. Walch et al[78] evaluated the postoperative results of 319 TSAs to assess the development of radiolucent lines around the glenoid. The patients were divided into 4 groups according to the extent of radial mismatch: (1) < 4 mm, (2) 4.5 to 5.5 mm, (3) 6 to 7 mm, and (4) 7 to 10 mm. The postoperative radiographs from each group were evaluated. At a mean follow-up of 53.5 months, they noted a linear relationship between radial mismatch and the incidence of glenoid radiolucency. The largest mismatch was associated with the fewest radiolucent lines. In addition, patients in group 3 had the highest mean Constant score. Walch et al concluded that implants with a radial mismatch of 6 to 7 mm provided the best combination of clinical results with a low incidence of postoperative radiolucent lines.

Glenoid malposition

Implanting the glenoid in a proper orientation is essential for long-term stability of the prosthesis. A malpositioned glenoid may have compromised fixation due to inadequate bony support or incomplete implant seating and may be subjected to increased torques on the fixation surface. Each of these destabilizing factors can result in early component loosening and clinical failure. Hopkins et al[32] conducted a FEA to evaluate the effect of glenoid alignment on cement mantle stresses in both normal and rheumatoid bone. They examined glenoids implanted centrally, anteverted, retroverted, inferiorly inclined, and superiorly inclined and reported that the potential for mechanical failure was lowest for glenoids oriented in a central position. Glenoids implanted in a superiorly or inferiorly inclined position had the highest probability of failure, and retroverted glenoids were more susceptible to loosening than anteverted components. A comparison between bone quality types (healthy vs rheumatoid) demonstrated that poorer bone quality amplified the tendency for loosening as a result of implant malposition.

In a smiliar FEA, Farron et al[24] evaluated the effect of varying component retroversion on glenoid loosening. Glenoid retroversion caused a posterior displacement of the glenohumeral contact point during rotational range of motion, leading to a major increase in micromotion (700% increase) and stress (326% increase) at the bone-cement interface compared with components implanted in a neutral orientation (Figure 7). Farron et al concluded that glenoid retroversion exceeding 10° should be corrected; adding, if correction is not possible, they recommend not implanting a glenoid.

Shapiro et al[67] compared the contact pressures in a healthy cadaveric shoulder, a TSA implanted in neutral, and a TSA implanted with the glenoid in 15° of retroversion. The retroverted shoulder was associated with significantly smaller contact area and significantly higher contact pressures compared with the native shoulder and neutral TSA. Shapiro et al concluded that uncorrected glenoid retroversion leads to eccentric loading and increases the likelihood of implant wear and loosening.

In addition to adversely effecting stability and fixation, implanting the glenoid in excessive retroversion may also adversely affect clinical outcomes. Yian et al[84] evaluated 47 cemented pegged glenoids using standard radiographs and CT scans at a mean follow-up of 40 months. Radiographs showed 21 of 47 glenoids had radiolucent lines, and CT scans showed 36 had radiolucent lines. They observed a significant correlation between greater preoperative glenoid retroversion measurements and poorer functional results. In addition, increased glenoid component retroversion was associated with significantly lower Constant scores.

Revision shoulder arthroplasty for glenoid component loosening

Outcome after revision surgery for glenoid loosening is commonly discussed in the literature. The possibility of glenoid resurfacing after revision for aseptic loosening depends largely on the available glenoid bone stock. Cheung et al[11] compared the outcomes of 33 shoulders in which the glenoid components were reimplanted and 35 shoulders in which the glenoid components were removed and bone grafting was done without reimplantation. Each patient group experienced pain relief after revision surgery; however, patients with glenoid reimplantation had improved active forward elevation and better Neer scores than those treated with implant removal and bone grafting.

Antuna et al[3] retrospectively evaluated 48 glenoid revision procedures in which 29 were revised for loosening, 14 were revised for implant failure, and 5 were revised for malposition or wear-associated instability. Within this cohort, 30 shoulders underwent glenoid reimplantation. Significant pain relief and improvements in active forward elevation and external rotation after revision surgery were reported. Patients in whom glenoid reimplantation was possible were significantly more satisfied and tended to have greater symptomatic and functional improvement compared with those treated with removal and bone grafting.

Deutsch et al[23] conducted a similar retrospective evaluation of 32 glenoid revisions, comparing the results of 15 glenoid reimplantations with those of 17 revised to a hemiarthroplasty. The reimplantation of a new glenoid component resulted in greater improvements in pain and postoperative external rotation compared with revision to a hemiarthroplasty. It is important to note, however, that these differences in outcomes may include a selection bias, because patients able to have a glenoid implanted potentially had better glenoid bone stock and a better soft tissue envelope than those revised to hemiarthroplasty.

The treatment strategy for revision cases in which intraoperative findings preclude immediate component reimplantation typically includes bone grafting to improve glenoid bone stock. Patients who continue to report pain with shoulder activity after component removal and grafting may be candidates for repeat revision with a glenoid component implantation after graft consolidation.[3,60]

Other considerations

Secondary to the challenges associated with obtaining a stable, durable and functional glenoid component during shoulder arthroplasty, some have proposed a nonprosthetic approach to managing the glenoid in cases of symptomatic degenerative arthritis. These alternatives include the ream-and-run procedure and biologic resurfacing.

Ream-and-run procedure

The ream-and-run procedure involves humeral hemiarthroplasty coupled with concentric reaming of the glenoid to a radius of curvature 1 to 2 mm greater than that of the humeral head prosthesis.[14] The ream-and-run procedure attempts to achieve glenohumeral stability by spherical reaming about the centerline of the glenoid to correct eccentric wear and minimize the potential progressive erosion and instability that has been reported with humeral hemiarthroplasty alone.[30]

Weldon et al[80] demonstrated in a cadaveric model that although denuding the glenoid of its cartilaginous surface reduced its contribution to glenohumeral stability, spherical reaming restored stability to values seen in both the native glenoid and those reconstructed with a polyethylene implant. The potential for a healing response and remodeling at the reamed glenoid surface was reported by Matsen et al[46] in a canine using the ream-and-run procedure. At 24 weeks after the procedure, a thick, firmly attached fibrocartilaginous tissue layer completely covered the glenoid surface articulating with the prosthetic humeral head.

In a recent case-control study comparing the ream-and-run procedure with that of standard TSA, Clinton et al[14] reported significant and comparable functional improvement in both patient groups. Patients in the TSA cohort had significantly higher scores on the Simple Shoulder Test at the 12-month follow-up; however, the scores were similar between the patient groups at both 2 and 3 years after surgery. Clinton et al concluded that although a longer recovery time was required, the ream-and-run procedure provided the opportunity for a comparable functional outcome without the potential risk of glenoid component failure.
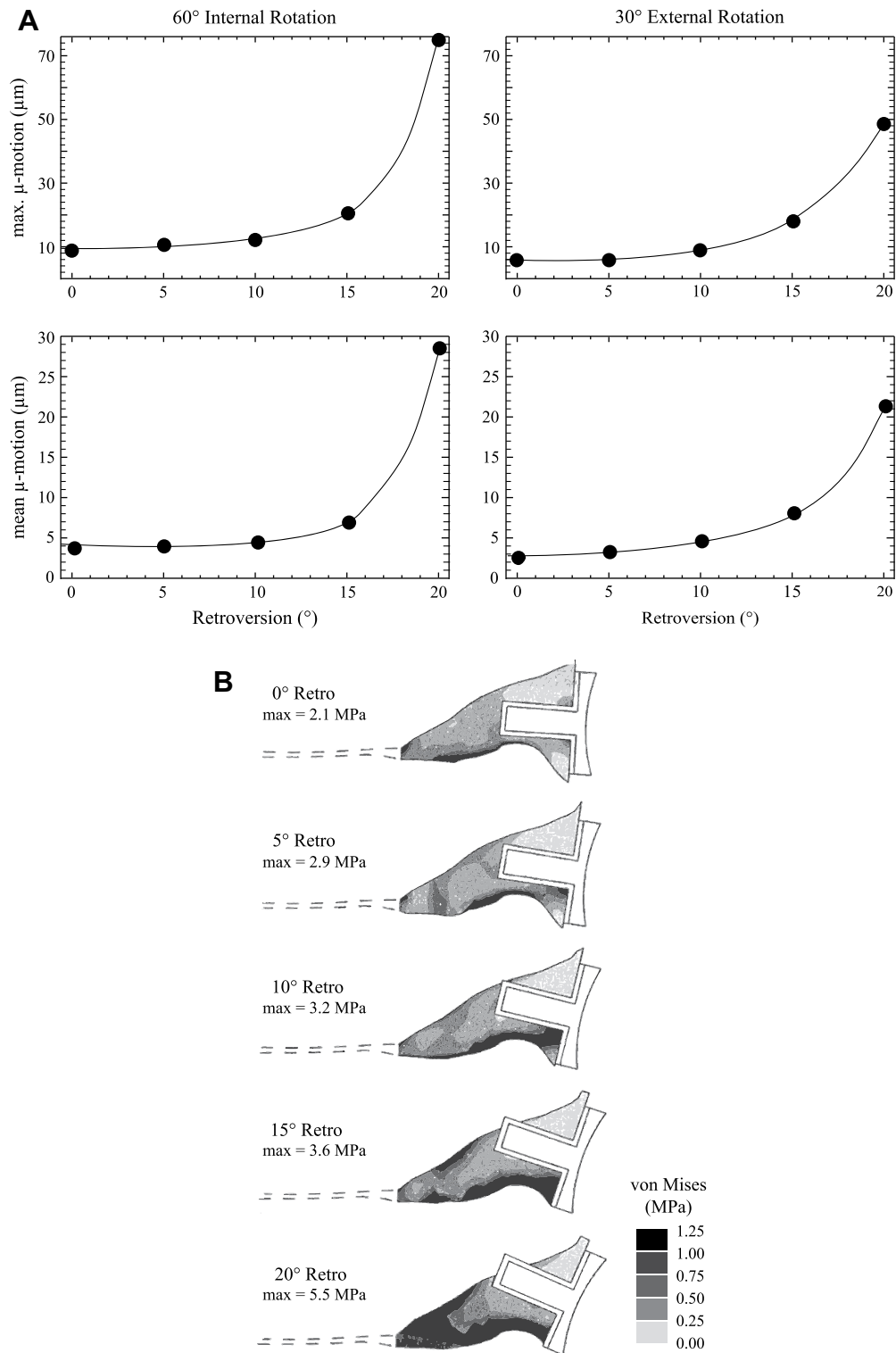
Figure 7 Implantation of the glenoid component in a retroverted position causes **(A)** a posterior displacement of the glenohumeral contact point leading to increased micromotion and **(B)** peak bone stress. (Adapted with permission from Farron et al. Risks of loosening of a prosthetic glenoid implanted in retroversion. J Shoulder Elbow Surgery. 2006; 15:521-526.)

Biologic resurfacing

Biologic resurfacing is an attractive alternative for treatment of degenerative arthritis of the glenoid, particularly for younger patients. Biologic resurfacing involves interposition placement of tissue between the glenoid surface and an implanted humeral hemiarthroplasty.[9] Tissue options include joint capsule, fascia lata, meniscal allograft

(preferably a lateral meniscus), Achilles tendon allograft, and synthetic materials (GraftJacket, Wright Medical, Arlington, TX).[9] Surgeons using biologic resurfacing techniques often prepare the native glenoid by reaming along the centerline to correct any pathologic alignment and provide a bleeding bony bed for tissue healing.

Creighton et al[21] evaluated the effect of an interposed lateral meniscal allograft on articular contact area and pressure in a cadaveric glenohumeral joint. They reported that the interposition of the lateral meniscus significantly decreased the stress in the underlying glenoid and spared glenoid contact centrally.

Ball et al[4] described their initial experience using meniscal allograft as interposition tissue combined with humeral hemiarthroplasty for 6 patients with glenohumeral arthritis. At a mean follow-up of 24 months, all patients were satisfied with the procedure and each achieved significant improvement in range of motion. No radiographic evidence of postoperative joint space narrowing was observed.

Nicholson et al[53] used lateral meniscal allograft resurfacing combined with humeral hemiarthroplasty in 30 patients with an average age of 42 years. At a mean follow-up of 18 months, they reported significant pain relief, improvement in active forward elevation and external rotation, and a high level of patient satisfaction. However, 5 complications (17%) did occur, all requiring reoperation during the first postoperative year.

Krishnan et al[39] used a mix of anterior capsule, autogenous fascia lata, and Achilles tendon allograft as their interposition tissue in their series of 36 shoulders treated with biologic resurfacing. At a minimum of 2 years of follow-up, the mean American Shoulder and Elbow Surgeons score was 91, a significant improvement from the preoperative mean of 39. Mean improvements were 70° in active forward elevation, 45° in external rotation, and 6 spinal segments in internal rotation. They concluded that biologic resurfacing provided younger patients with degenerative shoulder disease pain relief and allowed for maintenance of active shoulder function without the risk of glenoid implant wear or failure.

Managing the glenoid in young patients with arthritis

Glenohumeral degenerative disease in young, active patients presents a management dilemma for the treating orthopedic surgeon. Many recommend against implantation of a glenoid component in these patients because their active lifestyle may challenge the limits of the prosthesis. Surgical treatment alternatives for the young patient with glenohumeral arthritis include hemiarthroplasty, hemiarthroplasty combined with biologic resurfacing of the glenoid, the ream-and-run procedure, and rarely, shoulder fusion.[9,21,50]

Hemiarthroplasty performed alone has the potential to provide symptomatic relief and postoperative improvement in active range of motion. However, many have reported that progressive erosion of the glenoid occurs with time, leading to pain, limitation of motion, and poor function, often requiring reoperation.[21,42,59,70] Sperling et al[70] compared the outcomes of 78 hemiarthroplasties and 36 TSAs in 98 patients aged younger than 50 years. At a minimum follow-up of 5 years, both procedures provided patients with significant pain relief and improvement in active abduction and external rotation; no differences were noted between the treatment groups. However, radiographic follow-up demonstrated that glenoid erosion after hemiarthroplasty occurred in 68% of cases. In addition, 32 of 78 patients with hemiarthroplasty and 13 of the 36 patients with TSA had an unsatisfactory result. The Kaplan-Meier survival estimates for the hemiarthroplasties of 92% at 5 years, 83% at 10 years, and 73% at 15 years were lower than the survival predicted for the total shoulders of 97% at 5 years, 97% at 10 years, and 84% at 15 years. These results led Sperling et al to conclude that care should be exercised when offering shoulder arthroplasty to patients aged younger than 50 years.

As has been described, evidence is growing for successful nonprosthetic treatment options for young patients with shoulder arthritis. Although longer-term follow-up is necessary, biologic resurfacing and the ream-and-run procedure may prove to be the treatments of choice for this complex patient population.

Summary

Considerable attention has been devoted to better understanding the failure modes of glenoid components and to optimizing the design features and implantation techniques that maximize the opportunity of long-term fixation. As evidenced by a number of cadaveric studies, native glenoids have considerable anatomic variation. These natural variations and the anatomic changes associated with different shoulder pathologies add a level of complexity to the operative procedure as proper implant orientation and fixation are of vital importance to the survival of the implanted glenoid component.

A number of glenoid designs have been used by the different TSA systems. Although no definitive conclusions are made with respect to an optimal design, biomechanical and early clinical data indicate that pegged, curved-back, cemented prostheses with a radial mismatch of 4 to 7 mm provides an improved opportunity for stable long-term fixation, provided that it is implanted with the most advanced cement preparation techniques, in the proper version, and is fully seated. Future advancements in the design of biomaterials and

the fixation of noncemented glenoids may prevent joint overstuffing issues and reduce the incidence of glenoid loosening. For cases of symptomatic glenoid loosening, revision surgery with reimplantation of a new glenoid component when possible appears to be beneficial with respect to relieving pain and improving shoulder function.

Several nonprosthetic treatment options have been developed for young patients with glenohumeral degenerative disease that are receiving attention in the orthopedic surgery literature. Biologic resurfacing techniques and the ream-and-run procedure have shown promising early results, but longer-term evaluations are currently lacking and are needed.

A proper understanding of the anatomic and prosthetic variables involved with glenoid replacement allows shoulder surgeons to provide their patients the best opportunity for a positive outcome after TSA. Continued study of the biomechanics of the reconstructed glenohumeral joint, the factors associated with glenoid implant loosening, and nonprosthetic treatment options are necessary to optimize long-term outcomes.

Disclaimer

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