Planning software and patient-specific instruments in shoulder arthroplasty

James D. Wylie¹ · Robert Z. Tashjian¹

Published online: 25 January 2016
© Springer Science+Business Media New York 2016

Abstract Computer planning software and patient-specific instrumentation have been investigated in multiple subspecialties of orthopedics with mixed results. Shoulder arthroplasty has evolved over the last decade with improvements in implant design and surgical instrumentation. Despite these advances, glenoid positioning in shoulder arthroplasty continues to be a difficult problem. Recent advances in three-dimensional imaging techniques and the use of computer planning software may potentially address some of the common difficulties encountered by surgeons. The addition of patient-specific instrumentation and guides provide an option for patients with significant glenoid deformity that may allow improved accuracy of glenoid component implantation compared to using standard instrumentation. Studies have reported improved positioning of the glenoid component in both anatomic and reverse total shoulder arthroplasty with patient-specific instrumentation and guides. More research is needed to determine whether these improvements lead to better patient-reported outcomes or implant survival. In addition, further studies will be needed to address whether this technology is cost effective for large-scale implementation in the orthopedic community.

Keywords Shoulder arthroplasty · Reverse shoulder arthroplasty · Patient-specific instrumentation · Computer navigation · Glenoid positioning

This article is part of the Topical Collection on *Shoulder Arthroplasty*

✉ Robert Z. Tashjian
Robert.Tashjian@hsc.utah.edu

¹ Department of Orthopaedics, University of Utah, 590 Wakara Way, Salt Lake City, UT 84108, USA

Introduction

Anatomic total shoulder arthroplasty is the treatment of choice for end-stage glenohumeral primary osteoarthritis and has excellent surgical outcomes and survivorship [1]. It provides anatomic resurfacing of the glenohumeral articulation in an unconstrained fashion allowing the rotator cuff and deltoid to restore function [2]. In the setting of glenohumeral arthritis and a dysfunctional rotator cuff, reverse total shoulder arthroplasty results in a predictable return of function and pain relief [3]. Early efforts at reverse total shoulder arthroplasty were failures due to poor implant design. Grammont's redesign in the 1980s with a medialized glenosphere center of rotation laid the groundwork for the current prosthesis designs that have become the mainstay of treatment for patients with glenohumeral arthritis and rotator cuff dysfunction [4]. Because of the reverse ball and socket design, the shear forces created by the deltoid seen in an unconstrained anatomic arthroplasty in the setting of rotator cuff deficiency become compressive forces allowing the deltoid musculature to restore glenohumeral function and arm elevation [4].

The ideas of computerized planning software and patient-specific instrumentation are not new to orthopedics. The most commonly studied procedure is total knee arthroplasty. There have been conflicting reports of the efficacy of these innovations. Some studies have shown more anatomic implant positioning with both computerized planning/assistance and patient-specific instruments but no significant improvement in patient-reported outcomes or implant survival [5, 6]. Similarly, computerized planning for orthopedic trauma surgery has not shown any distinct advantage over conventional methods but has a significant learning curve, increased operative time, and increased cost [7]. Since there have not been consistent improvements in patient-reported outcomes using patient-specific instruments compared to traditional

instruments, these technologies have not been heavily adopted in orthopedic practice. The role of computerized planning software and patient-specific instruments and guides in shoulder arthroplasty has been a topic of interest recently in the literature. We will review the most recent advances in with regards to computerized planning and patient-specific instrumentation in shoulder arthroplasty as well as future directions.

Standard preoperative planning for shoulder arthroplasty

Standard preoperative planning for shoulder arthroplasty starts with a radiographic evaluation of the patient's glenohumeral anatomy. Standard two-dimensional radiographic images include shoulder anteroposterior (AP) view, true AP or Grashey view, scapular Y view, and axillary lateral view. The axillary lateral view can give the surgeon an idea of the glenoid wear pattern and the native version of the glenoid. The true AP view can give the surgeon an idea of the glenoid inclination. If the physical examination does not provide definitive information on rotator cuff function, then a magnetic resonance imaging exam of the shoulder can provide information to decide between anatomic (intact and functioning rotator cuff) and reverse total shoulder arthroplasty (torn and/or dysfunction rotator cuff). If glenoid deformity is suspected on two-dimensional radiographs, then a three-dimensional computed tomography (CT) scan of the shoulder can be obtained to further delineate the patient's altered glenoid anatomy. CT scanning will also allow preoperative computer planning for glenoid implantation.

The surgeon then can use these imaging exams to understand and plan for treatment of the patient's deformity intraoperatively. In the situation of an intact rotator cuff and implantation of an anatomic total shoulder arthroplasty, glenoid component positioning is commonly determined by placing a guidewire by hand perpendicular to the plane of the scapula in the axial and sagittal plane and parallel to the plane of the scapula in the coronal plane. Guidelines for final retroversion for glenoid implantation are controversial. Most surgeons will attempt to reduce glenoid retroversion to 10° to 15° as clinical and biomechanical data support increased risk for glenoid component loosening if the glenoid is placed in higher degrees of retroversion [8, 9, 10]. Farron et al. performed a study utilizing finite element modeling and determined that micro-motion at the bone-cement interface was strongly influenced by retroversion [8]. They determined that there was an exponential increase in maximal (+706 %) and mean (+669 %) micro-motion for internal and external rotation when the glenoid component was placed in greater than 10° of retroversion [8]. Shapiro et al. performed a biomechanical study with a custom cadaveric shoulder testing system and determined that placement of a glenoid component in 15° of

retroversion significantly decreased glenohumeral contact area and increased contact pressure compared to 0° of retroversion [10]. The authors hypothesized that glenoid component retroversion may result in eccentric loading and possibly lead to increased wear and loosening [10]. Finally, Ho et al. reviewed 66 total shoulder arthroplasties at a mean of 3.8 years postoperatively with radiographs [9]. In their cohort, 33 % of glenoids were implanted in greater than 15° of retroversion and 45 % of those were found to have osteolysis around the center peg consistent with early loosening. Of the remaining 67 % of glenoids implanted with <15° of retroversion, only 23 % were found to have osteolysis around the center peg [9]. The authors concluded that lucency around the center peg is correlated with component retroversion greater than 15°.

Methods currently available to restore retroversion to 10° to 15° or less include asymmetric glenoid reaming, bone grafting, or augmented components. Asymmetric reaming can be performed to address version abnormalities if retroversion is not severe. The amount of correction that can be performed is debated, but several cadaveric and computer simulation studies suggest that about 15° of correction can be obtained prior to glenoid vault violation [11–13]. Even if correction can be obtained, clinical data suggests that excessive reaming may increase the risk for glenoid loosening if the subchondral bone of the glenoid has been violated [14]. It is currently unclear how much bone removal is reasonable prior to compromising the long-term stability of the implant, although many would agree that correction of over 25° or 30° of retroversion requires an alternate method, either bone grafting (with or without changing implant type to a reverse shoulder prosthesis) or an augmented glenoid component. Bone grafting in the setting of anatomic total shoulder arthroplasty can be considered for high degrees of retroversion (>25° or 30°) in young patients (<60 years old), although clinical data suggests a higher early complication rate with this technique [15–17]. Reverse total shoulder arthroplasty with or without grafting for the highly retroverted glenoid and an intact rotator cuff is a more predictable operation with a lower complication rate although should only be considered in an older patient population (>60 years) [18]. Augmented glenoid components offer a solution for the highly retroverted glenoid that might otherwise be treated with an anatomic arthroplasty and bone grafting. There is limited historical data suggesting poor results with an augmented implant [19, 20]. There is no current clinical data on the current generation of augmented implants. Numerous biomechanical and computer simulation studies have been performed supporting the potential use of augmented implants, although clinical data is lacking [21–24, 25, 26]. Computer planning software and patient-specific instrumentation have the potential to dramatically improve the ability to accurately place a glenoid component (standard or augmented) with or without a graft in these severe cases.

If the rotator cuff is determined to be deficient with or without severe glenoid erosion, then the preoperative radiographs and CT scan can be used to plan proper placement of the glenosphere and baseplate. After glenoid exposure, the surgeon performs freehand or guided placement of the guidewire with approximately attempting to place the baseplate in neutral tilt. If there is severe central, posterior, superior, or anterior erosion, then bone grafting may be considered with placement of the reverse arthroplasty using humeral head autograft or allograft. It is unclear exactly how much baseplate contact is required with native bone to not require a bone graft although the authors would recommend bone grafting for any deficits larger than 25 %. Bone grafting in the setting of reverse total shoulder arthroplasty has lead to predictable results in multiple clinical series with low complication rates and high graft healing rates [27–30]. Care must be taken in the setting of reverse total shoulder replacement to assure placement of the glenoid baseplate and screws in to good quality scapular bone for good time-zero fixation to allow bone ongrowth. Computer planning and patient-specific instrumentation can potentially improve the accuracy of baseplate positioning, bone graft sizing and positioning, central post/screw and peripheral screw positioning, and lengths.

Common failure mechanisms of and difficulties in shoulder arthroplasty

In all forms of shoulder arthroplasty, the glenoid component is a common reason for early aseptic failure; therefore, accurate glenoid component placement is critical for long-term implant survival. In anatomic total shoulder arthroplasty, the glenoid component accounts for 24 % of all complications [31]. In addition, a recent systematic review demonstrated that asymptomatic radiolucent lines appeared at a rate of 7.3 % per year after primary TSA [32]. Subsequent symptomatic glenoid component loosening and component revision occurred at 1.2 and 0.8 % per year, respectively [32]. Metal-backed glenoid components have higher complications compared to all polyethylene components, consequently cemented all-polyethylene components have become the implant of choice for most surgeons [31, 32]. Revision shoulder arthroplasty universally leads to poorer outcomes when compared to the outcomes after a primary anatomic total shoulder arthroplasty, emphasizing the importance of getting the glenoid component correct at the primary surgical procedure [31, 33].

Similarly, correct glenosphere and baseplate placement and fixation in the scapula can be technically challenging in the setting of reverse total shoulder arthroplasty, especially in cases of severe bone erosion. Incorrect placement of the glenosphere can lead to early catastrophic baseplate failure, instability, and scapular notching which may be a cause

secondary implant loosening and functional decline [34]. The incidence of these complications can be mitigated by placing the glenoid baseplate on the inferior aspect on the glenoid, centered in the anterior/posterior sagittal plane, as close to neutral tilt as possible with avoidance of superior tilt [35]. Glenosphere placement too superior or in excessive anteversion or retroversion can predispose the component to scapular notching or impingement. Impingement of the implant on the scapula not only leads to notching but can also lead to dislocation of the prosthesis. Intraoperative glenoid fracture due to attempted placement of the central drill hole in an incorrect/eccentric position can lead to a situation that is unsalvageable. This can force the surgeon to revert to the placement of a hemiarthroplasty and allow for healing of the glenoid fracture before attempted revision to reverse arthroplasty. In the setting of severe glenoid bone loss and loss of anatomic landmarks, identification of the residual glenoid for baseplate fixation can be extremely challenging. Baseplate malposition can occur very easily in these cases especially in cases that require large structural bone grafts to augment regions of eroded bone. Identification of an alternative centerline with the central post or screw directed towards the scapular spine is a method to improve baseplate fixation as well in cases of bone loss, but determination of this line intraoperatively can be challenging [36]. All of these potential complications encourage the surgeon to pursue all means necessary for safe and effective placement of the glenoid component in both standard and reverse total shoulder arthroplasty.

Computer planning for shoulder arthroplasty

Investigations into computer planning for shoulder arthroplasty are in the early stages. Due to the difficulties with correct placement and potential complications of improper glenoid placement detailed above, surgeons have begun investigating computer planning for implant placement, especially in the patient with preexisting glenoid deformity. On this topic, there is relatively more information on anatomic total shoulder arthroplasty when compared to reverse total shoulder arthroplasty.

Early studies in computerized planning for shoulder arthroplasty investigated whether three-dimensional imaging aided surgeons in correctly identifying glenoid deformity. Scalise et al. showed that three-dimensional reconstructions of shoulder CT scans improved inter-rater reliability of glenoid bone loss and improved surgeons' ability to identify the zone of glenoid bone loss, make surgical decisions regarding glenoid preparation and component placement, and assess glenoid component fit [37]. A further study identified three-dimensional imaging methods along with regression equations that predict pre-osteoarthritic glenoid morphology using patient-matched contralateral non-diseased scapulae

[38]. In addition, it was determined that a patient's physiologic glenoid version could be accurately determined by three-dimensional imaging of their osteoarthritic shoulder [39].

The concept of using three-dimensional imaging developed into planning software to simulate glenoid component implantation using three-dimensional computer software. Multiple groups have reported the ability to use computer planning software to simulate glenoid implantation [11, 40•, 41•, 42•]. Both in bone models and actual surgical procedures surgeons demonstrated improved glenoid orientation with the use pre-operative planning software to guide implantation of the glenoid component [40•, 41•]. These authors were able to better place the glenoid component within 5° of desired inclination and 10° of desired version with three-dimensional templating and computer planning, compared to standard techniques in a randomized controlled trial of 46 patients [40•].

In reverse total shoulder arthroplasty, similar preliminary findings have been reported. Stubing et al. reported in a cadaveric study that glenoid baseplate positioning in the axial plane was improved by the use of three-dimensional navigation, with a mean deviation of 1.6° in the navigated procedure and 11.5° using conventional methods [43]. However, they did not find a significant difference in the coronal plane. Similarly, Venne et al. showed that computer planning and navigation allowed improved accuracy and precision of screw placement and improved precision of baseplate placement in a cadaveric lab study of reverse shoulder arthroplasty [44]. Appropriate placement of the glenoid component on post-implant imaging is reported in most of these studies of both anatomic and reverse implants. However, there have been no reports of improved patient-reported outcomes or implant survivorship in patients who had planning software utilized compared to conventional planning. Further studies are needed to confirm improved patient-reported outcomes and implant survivorship with this new technology.

One of the main challenges currently with three-dimensional planning or templating for both anatomical and reverse total shoulder arthroplasty is understanding how conventional two-dimensional measurements correlate with three-dimensional measurements (Fig. 1a, b). The typical two-dimensional measurements for version and humeral head subluxation have utilized the scapular axis as a basis. Based upon these two-dimensional measures, we have some guidelines regarding which patients have a higher risk for implant failure including patients with greater than 80 % posterior humeral subluxation and neoglenoid retroversion greater than 27° [45]. Unfortunately, there is variation between two-dimensional and three-dimensional measures both in regards to overall values as well as variability for both subluxation and retroversion. Budge et al. compared two-dimensional and three-dimensional measurements of retroversion and determined that two-dimensional

Fig. 1 **a** Baseline three-dimensional measurements of glenoid version and inclination utilizing computerized planning software (Blueprint, Tornier, Edina, MN). **b** Baseline humeral head subluxation as measured using three-dimensional planning software (*Green* represents humeral head volume posterior to central axis) (Blueprint, Tornier, Edina, MN). **c** Planned surgical case for implantation of a glenoid component (Blueprint, Tornier, Edina, MN). **d** Patient-specific guide created to be used to place a guide wire during glenoid preparation based upon a pre-operative three-dimensional plan (Blueprint, Tornier, Edina, MN)

and three-dimensional methods showed a high degree of both intraobserver and interobserver reliability although axial two-dimensional images were 5° to 15° different than the three-dimensional measures in almost 50 % of the measurements [46]. The authors reported that two-dimensional measures underestimate retroversion compared to three-dimensional measures by about 2° [46]. Terrier et al. reported that two-dimensional measures of retroversion underestimate three-dimensional measures by about 3° [47]. Jaxsens et al. compared humeral subluxation on two-dimensional and three-dimensional imaging and determined that two-dimensional measurements underestimated posterior subluxation compared to three-dimensional measures by about 3 % [48]. Understanding these differences will be necessary when utilizing historical two-dimensional measurement data to guide planning using three-dimensional measurements.

Similarly, understanding glenoid inclination will be critical in planning baseplate inclination during reverse shoulder arthroplasty. Typical guidelines for baseplate inclination are neutral tilt. These estimates are based upon a how the implant is positioned on a standing true AP radiograph which takes into account both glenohumeral position and scapulothoracic position. During computerized planning, scapulothoracic position is not accounted for therefore a correction for this is required. It is currently unclear what is the correct amount of planned three-dimensional inclination to place a reverse shoulder arthroplasty to account for scapulothoracic positioning in order to achieve a neutral tilt on a standing true AP X-ray. Further research is required to determine appropriate guidelines for three-dimensional planning of inclination of the reverse baseplate. Understanding these differences between two-dimensional and three-dimensional position both in regards to version, subluxation, and inclination is critical to avoid malposition.

Patient-specific instrumentation in shoulder arthroplasty

The development of three-dimensional imaging techniques and computerized planning for shoulder arthroplasty helps surgeons with planning for surgery; however, the development of patient-specific instrumentation has been introduced to allow improved surgical implementation of the preoperative plan (Fig. 1c, d). The premise of patient-specific

instrumentation to guide surgeons in implanting the glenoid component is using three-dimensional reconstructions of CT scans to build custom-made jigs for guide pin placement determined by the patient's bony anatomy. Typical landmarks for guide placement include the peripheral glenoid rim or base of the coracoid.

Multiple groups have published on the use of patient-specific instrumentation for shoulder arthroplasty [42•, 49•, 50•, 51, 52]. Two independent groups demonstrated improved glenoid component positioning in cadaveric shoulder samples. Walch et al. showed excellent correlations between the guide pin position on preoperative planning and those placed in 18 cadaveric scapulae using patient-specific instrumentation [42•]. Throckmorton et al. randomized scapulae to either conventional or patient-specific instrumentation for implantation of an anatomic total shoulder arthroplasty [52]. These authors found that there were significantly more malpositioned components in the conventional instrument group when compared to the patient-specific instrumentation group [52]. Clinical data has also been reported on the benefits of patient-specific instrumentation during anatomic total shoulder arthroplasty [49•]. Hendel et al. completed a randomized controlled trial of conventional versus patient-specific instrumentation for glenoid placement during anatomic shoulder arthroplasty [49•]. They found that patient-specific instrumentation significantly reduced the average deviation of implant position in both inclination and medial-lateral offset [49•]. The

greatest benefit was seen in patients with pre-surgical retroversion in excess of 16° where the average deviation in the conventional instrumentation group was 10°, while the average deviation was 1.2° in the patient-specific instrumentation group. Overall, the patient-specific instrumentation group had a lower incidence of malpositioned glenoid components and a significant improvement in the selection and use of the optimal implant for the specific glenoid anatomy [49•].

In reverse total shoulder arthroplasty, the evidence for patient-specific instrumentation is limited to cadaveric anatomic studies. Levy et al. used patient-specific guides in 15 cadaveric shoulders for glenoid baseplate placement and found them to be very accurate at reproducing a three-dimensional preoperative plan [50•]. However, they did not compare this to standard instrumentation. Throckmorton et al. randomized cadaver shoulders to standard versus patient-specific guides and found no significant difference in guide pin position between the groups [52]. There have been no clinical studies on patient-specific guides in reverse total shoulder arthroplasty.

Currently, there are several companies that provide the means of preoperatively planning for a surgical case and then creating a guide to be utilized during surgery to direct implantation (Table 1). Each system has slight differences in the planning tool as well as the shape of the guide created and landmarks used to reference the position of the guide at the time of surgery. Most systems require a CT scan of certain

Table 1 Table of currently available implant systems with 3D glenoid component planning and patient-specific instrumentation options

Company	System	Description
DJO® Global	Match Point System™	A comprehensive 3D planning software. CT scans can be uploaded and the surgeon can design a preoperative plan. Patient-specific instrumentation can then be ordered based on the preoperative plan. Options for both anatomic and reverse total shoulder arthroplasty
Zimmer®	Zimmer PSI Shoulder System™	A comprehensive 3D planning software. Surgeon devises the plan and PSI is created off of the preoperative plan. Only available for reverse total shoulder arthroplasty
Tornier	Blueprint™ 3D planning and PSI	A comprehensive 3D planning software. CT scans can be uploaded and the surgeon can design a preoperative plan. They can then decide whether PSI is needed and can be ordered based off of the preoperative plan. Only available for anatomic total shoulder arthroplasty
Zimmer BIOMET	Signature™ Personalized Patient Care Glenoid System	A comprehensive 3D planning software. CT scans can be uploaded and the surgeon can design a preoperative plan. PSI guides for glenoid guide pin placement are then ordered off of preoperative plan. Available for both anatomic and reverse total shoulder arthroplasty. A single guide is used for both anatomic and reverse shoulder arthroplasty in case a change in procedure is made intraoperatively
OrthoVis and Depuy	Glenoid Intelligent Reusable Instrument System	3D preoperative plan is devised based upon CT scan by engineers, which is sent to the surgeon for revision/approval. A custom instrument tray based upon the 3D plan is then shipped to the surgeon based upon the approved plan. Can be used for guide pin placement in both anatomic or reverse total shoulder arthroplasty

3D three-dimensional, CT computed tomography, PSI patient-specific instrumentation

specifications be performed and then three-dimensional reconstructions can be rendered for planning. Most systems allow direct surgeon planning in some form as opposed to having an engineer create the plan for the surgeon. Guides are then created based upon these plans and shipped for use during surgery with a typical delay of 3 to 4 weeks. Further data is required to determine if the improved accuracy of cases guided by patient-specific instrumentation will lead to improved clinical outcomes and implant survivorship since at this point it is only speculative.

Conclusions and future directions

Recent studies report improved anatomic placement of glenoid components in both cadaveric and clinical studies of total shoulder arthroplasty using computer planning and patient-specific instrumentation. Despite the theoretical benefits of improved accuracy of implant placement, clinical data supporting improved outcomes and implant longevity are lacking. While the lack of data is to be expected for such a new technology, it is unclear if the added cost will be clinically beneficial in the long term. Further study is needed to confirm that the improved anatomic positioning of these implants leads to improved patient-reported outcomes and improved survivorship of these prostheses over the long term. Cost-benefit and effectiveness analyses will need to be performed to determine whether this technology should be widely adopted or whether it should be reserved for select patients with more severe deformity.

Compliance with ethics guidelines

Conflict of Interest James D. Wylie declares that he has no conflict of interest.

Robert Z. Tashjian currently receives royalties from IMASCAP, a planning software company, as well as Shoulder Innovations, a company designing a total shoulder arthroplasty system.

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

1. Singh JA, Sperling J, Buchbinder R, McMaken K. Surgery for shoulder osteoarthritis. *Cochrane Database Syst Rev*. 2010;10, CD008089.
2. Wiater JM, Fabing MH. Shoulder arthroplasty: prosthetic options and indications. *J Am Acad Orthop Surg*. 2009;17:415–25.
3. Samitier G, Alentorn-Geli E, Torrens C, Wright TW. Reverse shoulder arthroplasty. Part 1: systematic review of clinical and functional outcomes. *Int J Should Surg*. 2015;9:24–31.
4. Boileau P, Watkinson DJ, Hatzidakis AM, Balg F. Grammont reverse prosthesis: design, rationale, and biomechanics. *J Should Elb Surg*. 2005;14:S147–61.
5. Sassoon A, Nam D, Nunley R, Barrack R. Systematic review of patient-specific instrumentation in total knee arthroplasty: new but not improved. *Clin Orthop Relat Res*. 2015;473:151–8.
6. Venkatesan M, Mahadevan D, Ashford RU. Computer-assisted navigation in knee arthroplasty: a critical appraisal. *J Knee Surg*. 2013;26:357–61.
7. Atesok K, Schemitsch EH. Computer-assisted trauma surgery. *J Am Acad Orthop Surg*. 2010;18:247–58.
8. Farron A, Terrier A, Büchler P. Risks of loosening of a prosthetic glenoid implanted in retroversion. *J Should Elb Surg*. 2006;15:521–6.
9. Ho JC, Sabesan VJ, Iannotti JP. Glenoid component retroversion is associated with osteolysis. *J Bone Joint Surg Am*. 2013;95. **Sixty-six total shoulder arthroplasties were evaluated with radiographs at an average of 3.8 years postoperative to determine factors affecting osteolysis around the central peg of an all-polyethylene press fit pegged glenoid component. Thirty percent of implants had osteolysis around the center peg at follow-up and excessive postoperative retroversion >15° was associated with an increased odds of osteolysis, whereas preoperative retroversion was not associated with no change in the odds of osteolysis.**
10. Shapiro TA, McGarry MH, Gupta R, Lee YS, Lee TQ. Biomechanical effects of glenoid retroversion in total shoulder arthroplasty. *J Should Elb Surg*. 2007;16:S90–5.
11. Nowak DD, Bahu MJ, Gardner TR, Dyrszka MD, Levine WN, Bigliani LU, et al. Simulation of surgical glenoid resurfacing using three-dimensional computed tomography of the arthritic glenohumeral joint: the amount of glenoid retroversion that can be corrected. *J Should Elb Surg*. 2009;18:680–8.
12. Gillespie R, Lyons R, Lazarus M. Eccentric reaming in total shoulder arthroplasty: a cadaveric study. *Orthopedics*. 2009;32:21.
13. Clavert P, Millett PJ, Warner JJP. Glenoid resurfacing: what are the limits to asymmetric reaming for posterior erosion? *J Should Elb Surg*. 2007;16:843–8.
14. Walch G, Young AA, Boileau P, Loew M, Gazielly D, Molé D. Patterns of loosening of polyethylene keeled glenoid components after shoulder arthroplasty for primary osteoarthritis: results of a multicenter study with more than five years of follow-up. *J Bone Joint Surg Am*. 2012;94:145–50. **Five hundred eighteen total shoulder arthroplasties with a cemented, keeled all-polyethylene glenoid component were evaluated retrospectively with radiographs at a mean of 122 months postoperative for humeral head subluxation, periprosthetic radiolucent lines and shifting of the glenoid component. Definite radiographic evidence of glenoid loosening was seen in 32 % of shoulders with subsidence and posterior tilting of the glenoid component associated with the use of reaming past subchondral bone to optimize glenoid component seating and position. The authors recommend preserving subchondral bone to maintain long-term longevity of the glenoid component.**
15. Sabesan V, Callanan M, Ho J, Iannotti JP. Clinical and radiographic outcomes of total shoulder arthroplasty with bone graft for osteoarthritis with severe glenoid bone loss. *J Bone Joint Surg Am*. 2013;95:1290–6.
16. Hill JM, Norris TR. Long-term results of total shoulder arthroplasty following bone-grafting of the glenoid. *J Bone Joint Surg Am*. 2001;83-A:877–83.
17. Klika BJ, Wooten CW, Sperling JW, Steinmann SP, Schleck CD, Harmsen WS, et al. Structural bone grafting for glenoid deficiency

- in primary total shoulder arthroplasty. *J Should Elb Surg.* 2014;23:1066–72.
18. Mizuno N, Denard PJ, Raiss P, Walch G. Reverse total shoulder arthroplasty for primary glenohumeral osteoarthritis in patients with a biconcave glenoid. *J Bone Joint Surg Am.* 2013;95:1297–304.
 19. Rice RS, Sperling JW, Miletti J, Schleck C, Cofield RH. Augmented glenoid component for bone deficiency in shoulder arthroplasty. *Clin Orthop Relat Res.* 2008;466:579–83.
 20. Cil A, Sperling JW, Cofield RH. Nonstandard glenoid components for bone deficiencies in shoulder arthroplasty. *J Should Elb Surg.* 2014;23:e149–57.
 21. Wang T, Abrams GD, Behn AW, Lindsey D, Giori N, Cheung EV. Posterior glenoid wear in total shoulder arthroplasty: eccentric anterior reaming is superior to posterior augment. *Clin Orthop Relat Res.* 2015;473:3928–36.
 22. Sabesan V, Callanan M, Sharma V, Iannotti JP. Correction of acquired glenoid bone loss in osteoarthritis with a standard versus an augmented glenoid component. *J Should Elb Surg.* 2014;23:964–73.
 23. Sabesan V, Callanan M, Sharma V. Guidelines for the selection of optimal glenoid augment size for moderate to severe glenohumeral osteoarthritis. *J Should Elb Surg.* 2014;23:974–81.
 24. Hermida JC, Flores-Hernandez C, Hoenecke HR, D'Lima DD. Augmented wedge-shaped glenoid component for the correction of glenoid retroversion: a finite element analysis. *J Should Elb Surg.* 2014;23:347–54.
 25. Knowles NK, Ferreira LM, Athwal GS. Augmented glenoid component designs for type B2 erosions: a computational comparison by volume of bone removal and quality of remaining bone. *J Should Elb Surg.* 2015;24:1218–26. **Three augmented component designs—full-wedge, posterior-wedge and posterior-step—were studied by virtual implantation in a cohort of 16 patients with B2 glenoids with version correction to 0° and 10°. Posterior wedge implants resulted in substantially less glenoid bone removal with the remaining supporting bone being better quality than a full wedge or posterior step component.**
 26. Kersten AD, Flores-Hernandez C, Hoenecke HR, D'Lima DD. Posterior augmented glenoid designs preserve more bone in biconcave glenoids. *J Should Elb Surg.* 2015;24:1135–41.
 27. Neyton L, Boileau P, Nové-Josserand L, Edwards TB, Walch G. Glenoid bone grafting with a reverse design prosthesis. *J Should Elb Surg.* 2007;16:S71–8.
 28. Melis B, Bonnevalle N, Neyton L, Lévine C, Favard L, Walch G, et al. Glenoid loosening and failure in anatomical total shoulder arthroplasty: is revision with a reverse shoulder arthroplasty a reliable option? *J Should Elb Surg.* 2012;21:342–9.
 29. Werner BS, Böhm D, Abdelkawi A, Gohlke F. Glenoid bone grafting in reverse shoulder arthroplasty for long-standing anterior shoulder dislocation. *J Should Elb Surg.* 2014;23:1655–61.
 30. Wagner E, Houdek MT, Griffith T, Elhassan BT, Sanchez-Sotelo J, Sperling JW, et al. Glenoid bone-grafting in revision to a reverse total shoulder arthroplasty. *J Bone Joint Surg Am.* 2015;97:1653–60.
 31. Gonzalez J-F, Alami GB, Baque F, Walch G, Boileau P. Complications of unconstrained shoulder prostheses. *J Should Elb Surg.* 2011;20:666–82.
 32. Papadonikolakis A, Neradilek MB, Matsen FA. Failure of the glenoid component in anatomic total shoulder arthroplasty. *J Bone Joint Surg Am.* 2013;95:2205.
 33. Deutsch A, Abboud JA, Kelly J, Mody M, Norris T, Ramsey ML, et al. Clinical results of revision shoulder arthroplasty for glenoid component loosening. *J Should Elb Surg.* 2007;16:706–16.
 34. Cheung E, Willis M, Walker M, Clark R, Frankle MA. Complications in reverse total shoulder arthroplasty. *J Am Acad Orthop Surg.* 2011;19:439–49.
 35. Lévine C, Boileau P, Favard L, Garaud P, Molé D, Sirveaux F, et al. Scapular notching in reverse shoulder arthroplasty. *J Should Elb Surg.* 2008;17:925–35.
 36. Klein SM, Dunning P, Mulieri P, Pupello D, Downes K, Frankle MA. Effects of acquired glenoid bone defects on surgical technique and clinical outcomes in reverse shoulder arthroplasty. *J Bone Joint Surg Am.* 2010;92:1144–54.
 37. Scalise JJ, Codsí MJ, Bryan J, Brems JJ, Iannotti JP. The influence of three-dimensional computed tomography images of the shoulder in preoperative planning for total shoulder arthroplasty. *J Bone Joint Surg Am.* 2008;90:2438–45.
 38. Ganapathi A, McCarron JA, Chen X, Iannotti JP. Predicting normal glenoid version from the pathologic scapula: a comparison of 4 methods in 2- and 3-dimensional models. *J Should Elb Surg.* 2011;20:234–44.
 39. Scalise JJ, Codsí MJ, Bryan J, Iannotti JP. The three-dimensional glenoid vault model can estimate normal glenoid version in osteoarthritis. *J Should Elb Surg.* 2008;17:487–91.
 40. Iannotti JP, Weiner S, Rodriguez E, Subhas N, Patterson TE, Jun BJ, et al. Three-dimensional imaging and templating improve glenoid implant positioning. *J Bone Joint Surg Am.* 2015;97:651–8. **Forty-six patients with 3D CT preoperative templating were compared to 17 patients with 2D imaging and templating with regards to achieving desired implant position. The use of 3D templating significantly improved achievement of the desired implant position within 5° of inclination or 10° of version when compared to 2D imaging.**
 41. Iannotti J, Baker J, Rodriguez E, Brems J, Ricchetti E, Mesih M, et al. Three-dimensional preoperative planning software and a novel information transfer technology improve glenoid component positioning. *J Bone Joint Surg Am.* 2014;96:e71–1. **Nine bone models from patients with glenohumeral arthritis were implanted with a glenoid component in vitro using standard instrumentation alone, standard instrumentation and 3D planning and a patient specific instrument and 3D planning. Postoperative 3D CT scans were made to register to the preoperative plan. The use of 3D planning with standard instruments improved accuracy of guide pin placement for the glenoid compared to no planning with standard instruments. The use of 3D planning with patient specific instruments further improved guide pin placement in comparison to 3D planning with standard instruments.**
 42. Walch G, Veziridis PS, Boileau P, Deransart P, Chaoui J. Three-dimensional planning and use of patient-specific guides improve glenoid component position: an in vitro study. *J Should Elb Surg.* 2015;24:302–9. **Eighteen cadaveric scapulae were imaged with CT and glenoid implants were placed virtually and patient specific guides were created to direct the central guide pin to position the glenoid. Glenoid component placement was performed and then postoperative CT scans were performed. Accuracy of glenoid component placement on final CT compared to preoperative plan was within 2° of planned inclination and version.**
 43. Stübig T, Petri M, Zeckey C, Hawi N, Krettek C, Citak M, et al. 3D navigated implantation of the glenoid component in reversed shoulder arthroplasty. Feasibility and results in an anatomic study. *Int J Med Robot Comput Assist Surg.* 2013;9:480–5.
 44. Venne G, Rasquinha B, Pichora D, Ellis RE, Bicknell R. Comparing conventional and computer-assisted surgery baseplate and screw placement in reverse shoulder arthroplasty. *J Should Elb Surg.* 2014;1–8.
 45. Denard PJ, Walch G. Current concepts in the surgical management of primary glenohumeral arthritis with a biconcave glenoid. *J Should Elb Surg.* 2013;22:1589–98.
 46. Budge MD, Lewis GS, Schaefer E, Coquia S, Flemming DJ, Armstrong AD. Comparison of standard two-dimensional and three-dimensional corrected glenoid version measurements. *J Should Elb Surg.* 2011;20:577–83.

47. Terrier A, Ston J, Farron A. Importance of a three-dimensional measure of humeral head subluxation in osteoarthritic shoulders. *J Should Elb Surg.* 2015;24:295–301.
48. Jacxsens M, Van Tongel A, Willemot LB, Mueller AM, Valderrabano V, De Wilde L. Accuracy of the glenohumeral subluxation index in nonpathologic shoulders. *J Should Elb Surg.* 2015;24:541–6.
49. • Hendel MD, Bryan JA, Barsoum WK, Rodriguez EJ, Brems JJ, Evans PJ, et al. Comparison of patient-specific instruments with standard surgical instruments in determining glenoid component position. *J Bone Joint Surg Am.* 2012;94:2167. **Thirty-one patients were randomized to glenoid component placement with 3D CT planning software and patient specific instrumentation or conventional CT scanning and surgical instruments. Postoperative CT scans were used to define and compare the actual implant location with the preoperative plan. The patient specific instrumentation decreased the average deviation of implant position for inclination and medial-lateral offset. The average deviation in version from the preoperative plan was 7° in the standard surgical group and 4° in the patient specific instrumentation group. In patients with preoperative retroversion**
- over 16°, the average deviation in version from the preoperative plan was 10° in the standard instrument group and 1.2° in the patient specific instrument group.
50. • Levy JC, Everding NG, Frankle MA, Keppler LJ. Accuracy of patient-specific guided glenoid baseplate positioning for reverse shoulder arthroplasty. *J Should Elb Surg.* 2014;23:1563–7. **Fourteen cadaveric shoulders were CT scanned and then a patient specific guide was created based upon a virtual preoperative 3D plan. Using the guide was then used and a post-procedure CT scan of the scapula was performed to compare the preoperative plan trajectory with the final position of the drill pathway. The drill pathway was within 1.2° of inclination and 2.6° of version of the planned pathway.**
51. Verborgt O, Vanhees M, Heylen S, Hardy P, Declercq G, Bicknell R. Computer navigation and patient-specific instrumentation in shoulder arthroplasty. *Sports Med Arthrosc.* 2014;22:e42–9.
52. Throckmorton TW, Gulotta LV, Bonnarens FO, Wright SA, Hartzell JL, Rozzi WB, et al. Patient-specific targeting guides compared with traditional instrumentation for glenoid component placement in shoulder arthroplasty: a multi-surgeon study in 70 arthritic cadaver specimens. *J Should Elb Surg.* 2015;24:965–71.