Review Article

Preoperative Planning for Anatomic Total Shoulder Arthroplasty

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ABSTRACT

The success of total shoulder arthroplasty is dependent on both proper patient selection and restoration of the native anatomy. After proper patient selection, preoperative planning is essential to select implants that will allow the surgeon to properly restore soft-tissue tension and correct for deformity. Although it is possible to template implants with plain radiographs, these do not allow accurate measurements of the complex three-dimensional anatomy of the glenohumeral joint. CT can be used to further examine version of the glenoid and humerus, as well as humeral head subluxation. Three-dimensional reconstructions also allow for virtual implantation, resulting in a more reliable prediction of implant appearance. Commercial software is available that calculates parameters such as version; however, these have been shown to have variability when compared with measurements obtained by surgeons. Patient-specific instrumentation can also be obtained based on preoperative measurements; however, although it allowed for improved measurements when compared with two-dimensional imaging, there has been no difference in version error, inclination error, or positional offset of the glenoid implant when comparing patient-specific instrumentation with standard instrumentation. Intraoperative navigation can also be used to give real-time feedback on implant positioning; however, additional studies are needed to fully evaluate its benefit.

Total shoulder arthroplasty (TSA) can offer long-term improvements in shoulder function and pain relief in patients with glenohumeral arthritis. The success of this procedure is dependent on proper patient selection and the surgeon's ability to restore the native anatomy. Optimal implant selection and placement requires the surgeon to consider the amount of glenohumeral bone loss and deformity. This is of particular concern on the glenoid side where bone stock in a severe deformity can be quite limited. In addition, the evaluation of the glenoid version and bone stock as well as assessment of the integrity of the rotator cuff can aid surgeons in deciding between conducting anatomic versus reverse TSA. Given the complexity of the scapular anatomy and its orientation, advanced imaging is typically used to plan version correction that is required for the glenoid implant. Historically, the position of the glenoid implant is set using a guidewire and freehand reaming. Recent technological advances have allowed for the use of three-dimensional (3D) imaging, 3D-printed models, patient-specific instrumentation, and intraoperative navigation to accurately place the glenoid implant. Meanwhile, humeral implant positioning is focused on restoring humeral height and retroversion while also ensuring proper soft-tissue balance. Preoperative imaging and templating can also aid in reliably restoring these parameters.

Importance of Implant Placement

Most patients who undergo TSA for glenohumeral arthritis report good-to-excellent outcomes, but less than satisfactory results can occur. Many factors influence patient outcomes including preoperative motion, rotator cuff function, and severity of arthritis (posterior glenoid erosion and humeral head subluxation).[1] Early failure of the glenoid implant is the most common mode of failure in TSA and can be influenced by the aforementioned risk factors.[1-3] The proper placement of TSA implants, however, is one of the factors that can improve outcomes and reduce the risk of such glenoid loosening and is dependent on proper preoperative planning and surgical execution. Studies have described an increased risk of implant impingement when parameters of glenoid inclination, inferior-superior position of the humeral head, and prominence of the humeral calcar are not properly accounted for during the placement of TSA implants.[4-6] Multiple studies have demonstrated that such impingement can result in such early glenoid loosening. This is a greater concern in the setting of more severe deformity where the placement of implants is even more difficult. Iannotti et al[7] noted that a glenoid retroversion of 20° or more can result in center peg perforation with the placement of the glenoid implant. In such situations, restoration of version may require the use of bone grafting or augments.

Radiographic Imaging of the Shoulder

Plain Radiographs

The traditional evaluation of patients with glenohumeral arthritis includes multiple plain radiographs. Anteroposterior , Grashey (“true” anteroposterior), scapular-Y, and axillary views are the typical views of a shoulder series used to help evaluate joint space narrowing, posterior glenoid wear, and version. In particular, the axillary view is often used for evaluating the glenoid vault. A proper axillary view can help demonstrate the amount of asymmetric wear that is often seen in the setting of more advanced disease where deficiency in the posterior glenoid and subsequent subluxation of the humeral head may need correction. This is done with the arm in abduction (preferably at 90°), which is not always possible with an arthritic shoulder. The Grashey view projects the radiograph beam anteroposterior to the scapula rather than the front of the patient. This requires rotating the patient 35° to 45° to account for the angle of the scapula. In combination with the axillary view, the Grashey view is beneficial for assessing the amount of true cartilage wear and medialization of the joint line by evaluating various radiographic landmarks and measurements (Figure 1).

Computed Tomography

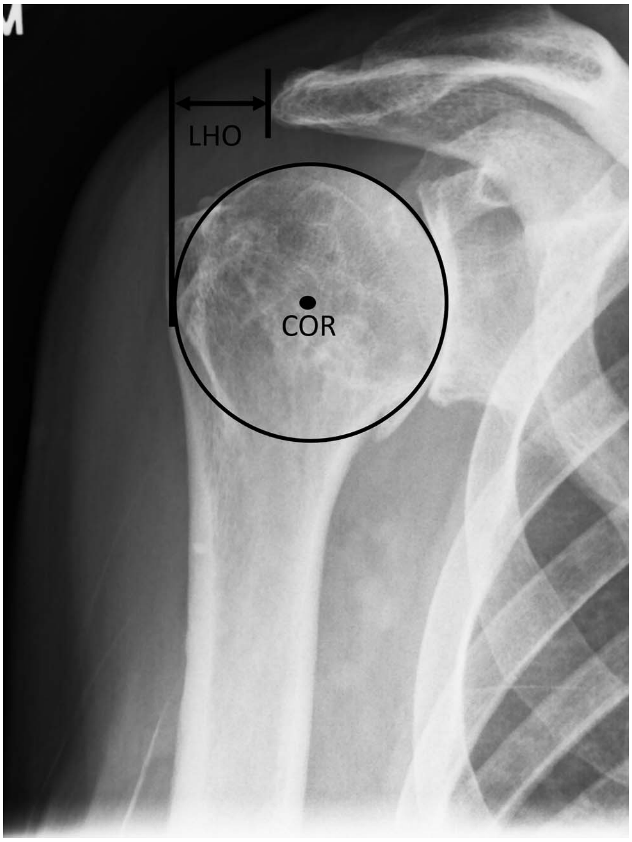
The use of CT has become much more common for the preoperative assessment of an arthritic shoulder as the use of templating software has evolved. In addition, there can be limitations with the use of plain radiographs due to the incorrect trajectory of the radiograph beam or the inherent limitations of a two-dimensional (2D) projection of a 3D object, which can be accounted for in CT scans. Nyffeler et al[8] compared axillary views with 2D CT scans and found that glenoid retroversion was overestimated in 86% of cases, with the mean difference in version on plain radiographs 6.5° greater than those on CT scans. For optimal evaluation and planning for reconstruction, it is recommended that the imaging cuts be oriented perpendicular to the surface of the glenoid, noting that the scapula is typically oriented in 20° to 30° of anteversion with respect to the coronal plane.[9,10] Unfortunately, this proper positioning is not always achieved and can lead to miscalculation of glenoid measurements.[10] Bryce et al[10] found that although clinical CT scans were often aligned axially with a patient’s torso, they were almost never perpendicular to the scapular body, which resulted in mismeasurement; for every degree of scapular coronal abduction, there was a corresponding 0.42° of glenoid anteversion. For cases involving the traditional B2 biconcave glenoid, improper orientation of the CT images can lead to overestimation of version and inclination.[11] Such concerns have led many authors to endorse the use of 3D reconstructions, which allows images to be processed and analyzed, regardless of the patient or extremity position.

Radiographic Review and Considerations

Traditional Radiographic Measurements and Humeral Head Sizing

Restoring the humeral head anatomy and center of rotation (COR) is necessary to avoid implant loosening

Figure 1



Radiograph showing a standard anteroposterior Grashey view demonstrating landmarks and measurements of the center of rotation (COR) and lateral humeral offset (LOH), which can help in understanding medialization of the joint line.

and restore range of motion. Deviations from the anatomic COR most often result in a medialized COR or overstuffing of the humeral implant, resulting in altered glenohumeral mechanics.[12] Such overstuffing can lead to increased stress on the rotator cuff and result in early failure. Studies have shown that as few as 2.5 mm of superior translation of the humeral head may lead to impingement.[5] The humeral head height, neck-shaft angle, and radius of curvature are often used to determine the premorbid anatomy; however, this is often a challenge in an arthritic humeral head. For this reason, nonarticular landmarks are used to determine premorbid humeral head size and plan for implant sizing and selection. The circle-fit technique uses a true anteroposterior radiograph of the glenohumeral joint and identifies three bony landmarks: the lateral cortex of the greater tuberosity, the medial calcar at the point where it meets the articular surface, and the medial edge of the greater tuberosity. A circle is drawn that intersects these three landmarks.[12] These landmarks can also be used to create a sphere (Figure 2), which is useful when conducting an intraoperative evaluation. This method most reliably predicts the radius of curvature; however, the variations seen for the humeral height and neck-shaft angle are within the range of commercially available implant sizes.[13]

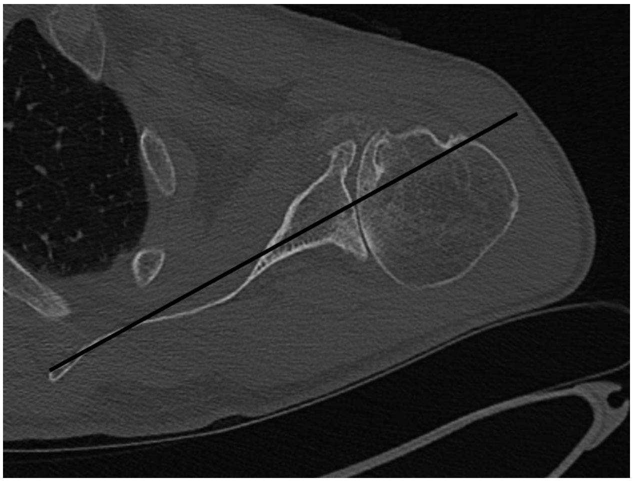
Humeral Head Subluxation

In addition to proper sizing of the humeral head, the appreciation of its position relative to the glenoid is also of great importance. Proper restoration of the humeral head can help to balance soft tissues responsible for this relationship, but the morphology of the glenoid itself is also largely responsible. Two common methods are used to measure the amount of humeral head subluxation on a CT scan. The scapula axis method measures the anteroposterior length of the humeral head located posterior to the scapular axis (Friedman line) compared with the anteroposterior diameter of the humeral head (Figure 3). The mediatrice method uses a similar calculation; however, the reference line is perpendicular to the middle of the glenoid joint surface. This method is considered more of a glenohumeral axis rather than the scapulohumeral assessment of the Friedman line. A ratio greater than 55% is defined as posterior subluxation. When comparing both

Figure 2

Radiograph showing an anteroposterior Grashey view demonstrating the "perfect circle" of the humeral head.

Figure 3



Radiograph showing an axial CT cut demonstrating posterior humeral head subluxation using the Friedman line as a frame of reference. Note the larger amount of humeral head posterior to the line than anterior.

methods, the former scapulohumeral method has shown to have higher intraobserver reliability.[14]

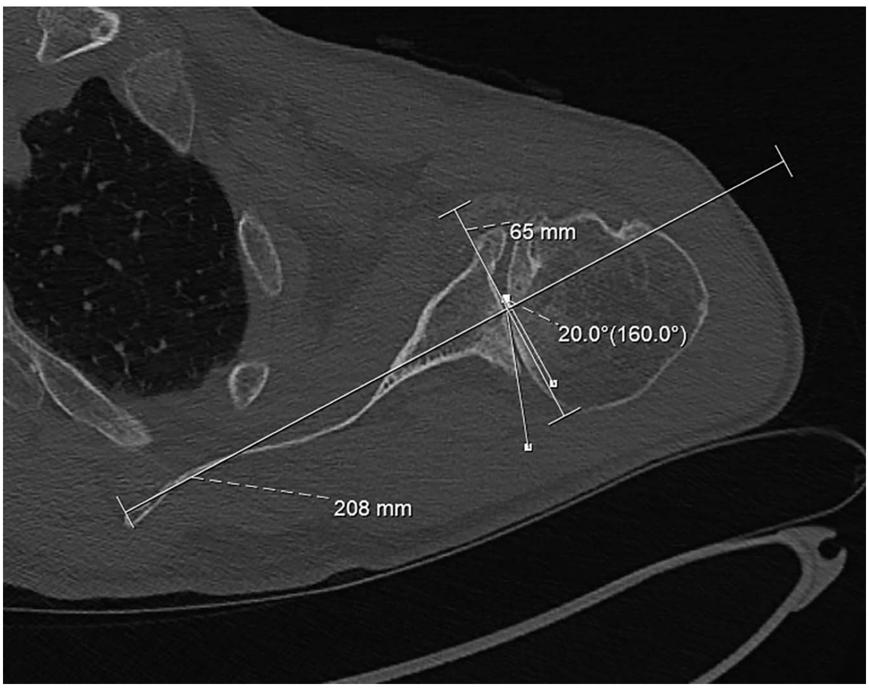
Glenoid Version

Several methods have been described to measure version based on CT imaging. The technique described by Friedman et al[15] uses the scapular axis, drawn from the midpoint of the glenoid fossa to the root of the scapular spine on an axial CT cut. This axis is typically chosen on the axial image of the glenoid just inferior to the coracoid process. A line drawn perpendicular to the scapular axis is considered the neutral version. The angle formed between the line of neutral version and a line between the anterior and posterior margins of the glenoid represents the version. More posterior wear of the glenoid results in retroversion, which is represented in negative degrees (Figure 4).

Glenoid Wear: The Walch Classification

The most used assessment of glenoid morphology is the Walch classification (Figure 5), which was initially described in 1999 using 2D CT imaging.[16] Walch originally described three main morphologic types: type A, in which the humeral head was centered; type B, in which the humeral head was subluxated posteriorly; and type C, characterized by a glenoid retroversion of at least 25°. Type A was further subclassified into A1 or A2 for minor or major central glenoid erosion, respectively. Type B glenoids were subdivided into types B1 and B2, with B2 glenoids demonstrating a biconcave morphology. Since its inception, the Walch classification has evolved with more categories and subtypes of glenoid morphology appreciated by the accuracy of more advanced imaging.

Figure 4



Radiograph showing an axial CT cut demonstrating posterior glenoid wear and retroversion with respect to the Friedman line.

Figure 5

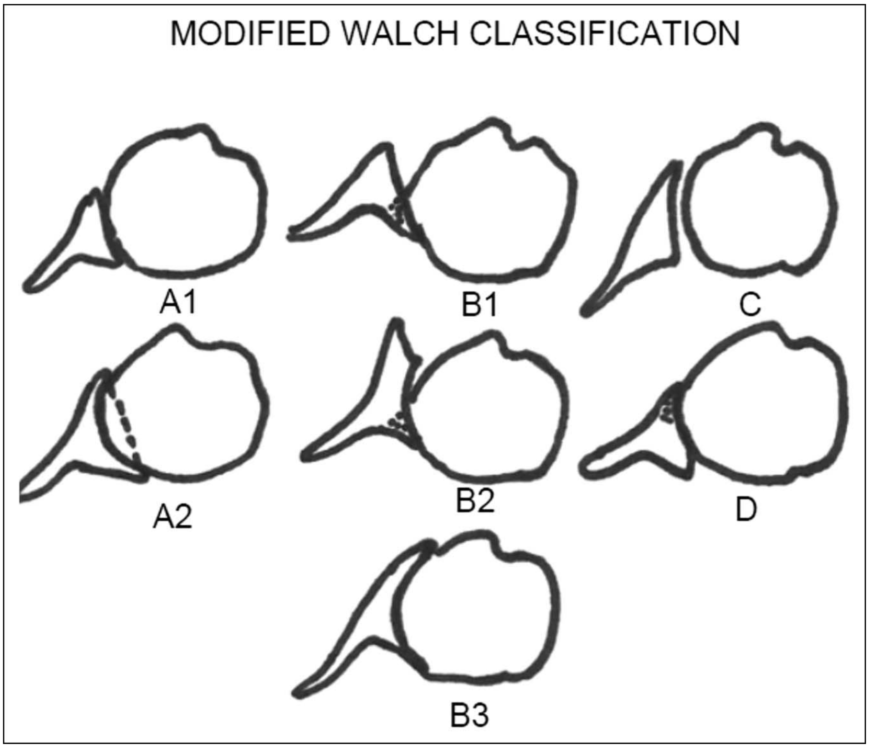


Diagram showing the Walch classification of arthritic glenoid deformity.

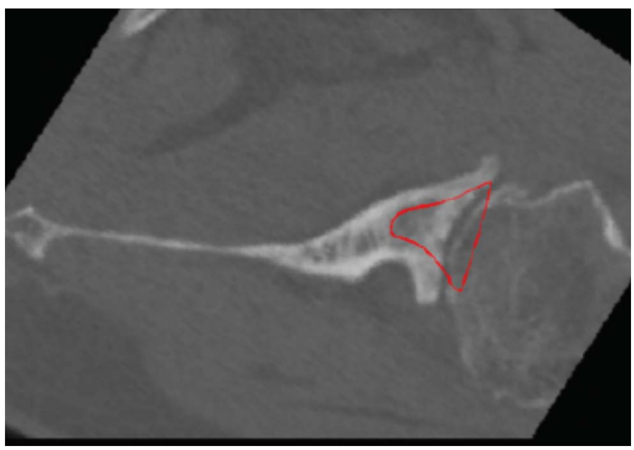
In 2016, Bercik et al[17] described the B3 and D glenoids in an effort to increase the interobserver and intraobserver reliability. B3 glenoids are characterized by posterior wear and a monoconcave articular surface, with at least 15° of retroversion or 70% posterior humeral head subluxation. Type D glenoids are characterized by any level of glenoid anteversion.[17] The following year, Iannotti et al further described the B3 glenoid as one that has a high pathologic retroversion, normal premorbid version, and acquired central and posterior bone loss that is typically greater than that seen in a B2 glenoid. In addition, the authors further categorized type C glenoids with a C2 glenoid that is dysplastic with high pathologic retroversion, high premorbid version, and acquired posterior bone loss, which leads to a biconcave appearance.[18]

Glenoid Vault Model

More recently, the vault model was developed to avoid version measurement differences acquired from scapular body variations and is the alternative in cases where a CT scan does not incorporate the body of the scapula. The use of this model also is helpful in determining the Walch classification in patients with notable posterior bone loss or dysplastic glenoids.[19] Similar to the Friedman method, a line is drawn from the anterior to posterior margin of the glenoid, referred to as the glenoid line. The glenoid vault axis is defined as a line connecting the center of the glenoid line and the scapular vault (Figure 6). The angle formed between a line perpendicular to the glenoid vault axis and the glenoid line is the version.

Poon and Ting[20] also developed a vault measurement method based on a mid-glenoid axial CT slice. An isosceles triangle is drawn in the medial end of the

Figure 6



Radiograph showing an axial CT cut of the glenoid demonstrating the vault model.

Figure 7

Radiograph showing three-dimensional reconstruction of the glenoid and humeral head from software conversion of a two-dimensional CT scan.

glenoid endosteal vault. A line that bisects the triangle is then drawn, followed by a line perpendicular to it, which defines neutral version. The angle formed between the line of neutral version and a line parallel to the glenoid endosteal face is the version. Using the glenoid endosteal face as opposed to the articular surface removes the potential for variations in measurements due to osteophytes. This method demonstrated more precision in measurements when compared with the vault model based on the Friedman line. Both models have demonstrated larger retroversion values in normal and arthritic shoulders compared with traditional methods of glenoid version measurement.[20]

Preoperative Total Shoulder Arthroplasty Templating

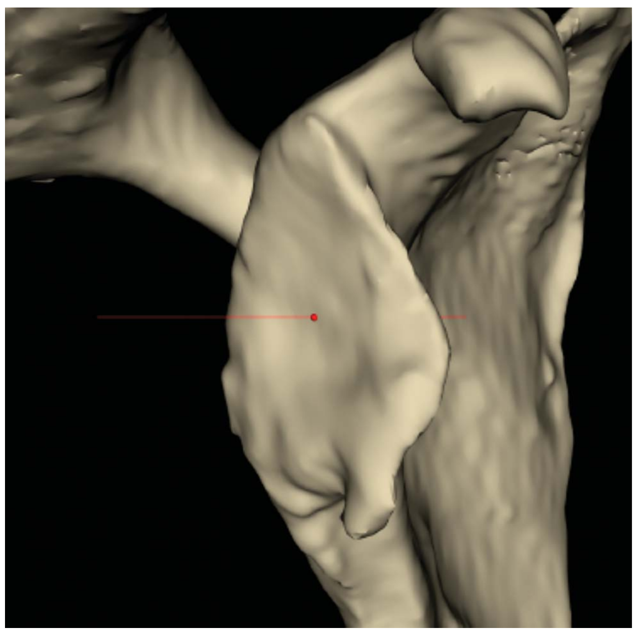
Standard Templating Based on Plain Radiographs and 2D CT

Plain radiographs may be used for preoperative planning if the surgeon understands their limitations. These radiographs do not allow the surgeon to visualize the medial border of the scapula, however, which limits the ability to calculate glenoid version based on the previously mentioned methods. Radiographs may also overestimate retroversion in 86% of cases.[8] In addition, different beam orientations can result in variability in measurements by making radiographic landmarks hard to see. Magnified templates available from manufacturers can be superimposed onto calibrated plain radiographs for preoperative planning. This results in better accuracy for determining humeral stem size when compared with humeral head size, with accurate prediction of humeral head size in 44% to 66% of cases.[21]

Templating can also be done on a digital anteroposterior glenohumeral radiograph using software that allows the user to superimpose implants onto the image. This results in similar accuracy when compared with analog templating, with 53% accuracy of templated head size and 77% accuracy of stem size to one size variation.[22]

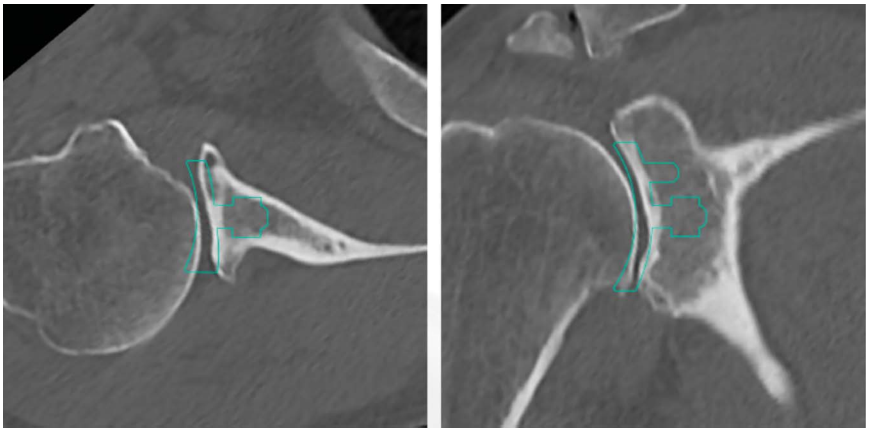
A 2D CT scan can be used to determine glenoid version, as previously described. These measurements can then be combined with traditional methods to estimate the required version correction angle intraoperatively.

Figure 8



Radiograph showing a software three-dimensional reconstruction of the glenoid with central pin placement for the reaming axis.

Figure 9



Radiographs showing CT images demonstrating software-guided positioning of an augmented glenoid implant.

Based on anatomic landmarks, the surgeon estimates the pin placement needed before reaming to obtain the required correction. Although optimal glenoid implant position can be achieved in cases of minimal deformity, a preoperative glenoid retroversion of 10° prevents consistent placement of the glenoid implant within 10° of the ideal retroversion.[23] When comparing preoperative planning done on 2D imaging, re-evaluation with 3D reconstruction resulted in a change of implant selection in 14% of cases and a change from planned TSA to reverse TSA in 8% of cases.[24] Such modern 3D imaging modalities have accelerated the evolutions of modern shoulder arthroplasty templating.

Modern Shoulder Arthroplasty Templating

3D Imaging

Templating with 3D reconstructions of imaging allows for virtual implantation, which facilitates visualization of selected implants and results in more reliable prediction of implants. Preoperative planning using 3D reconstruction of a 2D CT scan can match the selected glenoid size, head size, and head thickness 100% of the time when compared with those selected preoperatively.[25] Both manufacturer-specific and independent preoperative planning software programs are available. A comparison of software programs has been shown to reliably predict humeral head size; however, variations were present when determining humeral head height.[26]

Manual Segmentation

Creating a 3D model for templating was initially done by taking 2D CT scans and manually reformatting the images to create an appropriate anatomic model. Kwon et al demonstrated this using cadaveric scapulae in which the authors referenced glenoid version from the scapular plane. The authors defined this plane using the intersection of the medial scapular border with the scapular spine, the center of the glenoid fossa, and the inferior tip of the scapular body. The version measures from the 3D images were within 1° of the actual measures from the cadaveric specimen.[27] Subsequently, many other authors have described various methods of determining 3D version using various landmarks. Lewis and Armstrong[28] defined version as the angle between the scapular plane and the radial line connecting the center of the humeral head with the center of the glenoid fossa. They found this "sphere fit version" to be within 1.5° of the standard mid-glenoid version. The issue with these measures is that biconcavity or glenoid osteophyte can cause discrepancy in the location of the anatomic points used to define these planes and lead to variations in version. In addition to these concerns, the manual segmentation of 2D images into 3D reconstructions is highly criticized. The process is time-consuming, depends on the expertise of the surgeon or an engineer analyst, and requires cooperation and coordination between an engineer and a surgeon. This can be costly both for time and money.

Automatic Segmentation

The evolution of modern templating software has exploded in recent years with multiple implant designers offering their own software programs to allow for virtual preoperative planning using patient imaging studies. A standard thin slice (<1 mm) 2D CT scan obtained by a patient is reformatted by these various software programs with 3D reconstruction of the glenoid and humerus to help identify accurate landmarks and assess version, inclination, and subluxation (Figure 7). In addition, these programs allow for virtual implantation of glenoid and humeral implants into the 3D bone reconstructions. Surgeons can assess guide pin placement into the glenoid (Figure 8), whether there is center peg perforation risk, and even determine the need for augmented implants in cases of significant posterior glenoid wear (Figure 9).

Comparison of Software Measurements

Measurements for glenoid version, glenoid inclination, and humeral head subluxation have been shown to be markedly different between those obtained by surgeons when compared with those obtained with commercial software programs. Denard et al evaluated the measured version and inclination of 63 patients between two commercially available 3D planning programs and found that a difference of ≥5° occurred in 30% and 46% of cases, respectively. In addition, nearly a quarter of those cases had a difference of ≥10° between the two programs.[29] A subsequent study by Erikson et al compared four commercially available software programs with the assessment of five fellowship-trained surgeons. The authors noted that in the 81 cases evaluated, there was notable difference in measures of the software programs to measures obtained by the surgeons in version, inclination, and subluxation. The software programs tended to show increased measures of superior inclination, retroversion, and posterior subluxation. Measurements obtained by surgeons demonstrated higher inter-reliability.[30] Although software programs may produce reliable measurements, surgeons should be aware of the inherent tendencies of the software systems to skew these values and be prepared to account for this intraoperatively. In addition to using a templating software of choice, it is recommended that surgeons analyze advanced imaging studies independently and appreciate bony anatomy free of any software influence. Although this may lead to a variation of the intraoperative plan, it is a thorough and responsible way for surgeons to preoperatively plan rather than just use a “plug and play” approach with industry software.

Patient-specific Guides and Navigation

Patient-specific Instrumentation

Patient-specific instrumentation (PSI) is based on the glenoid morphology from a preoperative CT scan and a selected glenoid implant. A 3D CT model is created from a 2D scan, and depending on the software, a plan for glenoid pin placement is either automatically selected or manually determined by a surgeon. The instrumentation is designed to engage a specific landmark on the pathologic glenoid to guide implant placement. The instrumentation can either be designed for a specific patient or be reusable. Reusable PSI consists of equipment that is adjustable intraoperatively to the patient’s anatomy. This can be by the use of either an adjustable guidewire or a base. Iannotti et al[31] demonstrated the use of a reusable instrument that consists of a cannulated handle with adjustable legs that are placed on a physical 3D model of the patient’s glenoid, locked into place, and then used in the intraoperative setting. The authors found that the combination of 3D templating and the reusable PSI resulted in a more accurate glenoid implant compared with 2D imaging and standard instrumentation. However, the use of the PSI afforded no greater accuracy compared with standard instrumentation.[31] The senior author later published results that demonstrated again no difference in the accuracy of glenoid placement when using 3D models and PSI when compared with standard instrumentation.[32] Subsequently, single-use PSI has also been evaluated. Suero et al described the use of custom glenoid implant guides using 3D imaging of the patient’s anatomy. The glenoid implant was imported into the 3D software, and based on the surgeon’s preferred position, a guide was manufactured that conformed to the patient’s glenoid and included a central hole for guidewire placement.[3] PSI used in in vivo TSA results in an average deviation of 2.6° from the planned glenoid version and 1.0° from the planned glenoid inclination. The average deviation in the anteroposterior and superoinferior positions of the glenoid implant was 0.5 mm. Although the clinical significance of these values was not defined, they represent small absolute values.[33] A recent meta-analysis revealed no difference in version error, inclination error, or positional offset of the glenoid implant when comparing PSI with standard instrumentation.[34] Although these studies support the use of 3D imaging and either standard instrumentation or PSI for more accurate glenoid placement when compared with 2D imaging, they have not consistently determined the benefit of PSI when compared with standard instrumentation in the presence of 3D imaging.[23,31] This would suggest that the use of an accurate 3D model has more influence on proper implant positioning than the PSI. In addition, creating single-use PSI can be associated with delays in the planned surgical date, with studies reporting production times varying from 2 to 5 weeks.[34] Given the increased short-term cost, time constraints, and overall lack of data demonstrating improvement in clinical outcomes, the overall benefits of PSI use are yet to be determined. It is worth nothing, however, that PSI may also be more valuable for surgeons who conduct a lower volume of TSAs because surgeons with higher volume may not have inherent variability when using implants and instrumentation. For lower volume surgeons, the added guidance of PSI can help increase implant placement accuracy because they are less familiar with subtle variations in bony anatomy.

Intraoperative Navigation

Navigation systems use a computer-based system that registers bony landmarks and correlates those with a standard coordinate axis to help guide the surgeon in real time. Intraoperative navigation has been described both with and without the use of imaging. Image-free systems use optical trackers on instruments which can detect change in angles, thus allowing the surgeon to measure a real-time change in glenoid version or inclination. Imaging is displayed on a separate monitor that allows the surgeon to see and confirm planned resections before making cuts or reaming. Both require additional instrumentation, and the use of image-based navigation requires an additional computer unit. Two studies found that the use of navigation increased surgical time by an average of 6 to 31 minutes.[35,36] Although neither study described intraoperative or postoperative complications, the authors reported a failure of the navigation system to correctly identify landmarks in some of the patients. Contrarily, improvements in the correction of glenoid retroversion have been reported on a prospective trial with a small patient population.[35] Recent meta-analysis also found that surgical navigation and patient-specific instrumentation improve positioning of the glenoid implant, however, with notable heterogeneity of results across the studies examined.[37] Studies also support that navigation more accurately recreates the preoperative glenoid placement, which has been described as a limitation of only using 3D imaging for implant placement planning.[38,39] These early reports in the literature suggest that intraoperative navigation is useful in providing accurate real-time implant placement, but additional studies demonstrating its value are warranted.

Robotic-assisted Surgery

Robotic-assisted surgery in unicompartmental and total knee arthroplasty was developed to improve implant alignment with the goal of improved implant survivorship and functional outcomes. During robotic-assisted surgery, an optical tracking system is used in conjunction with preoperative CT images that are specifically formatted to implant manufacturer specifications. Although short-term studies have shown high survivorship and patient satisfaction, long-term clinical outcome studies are lacking.[40] It is worth noting that inferior outcomes have not been demonstrated. There is a theoretical benefit in reducing the amount of instrumentation and inventory and thus resulting in net cost savings. This may be advantageous as indications for TSA are expanded to younger and more active patients. However, there are currently no commercially available options for robotic-assisted TSA.

Summary

The utilization of templating in shoulder arthroplasty continues to evolve and has been demonstrated to help surgeons with the accurate placement of TSA implants. Admittedly, the focus of these templating tools has been on the glenoid implant because this remains the most common mode of failure. As humeral implant design evolves with the advent of short-stemmed and stemless implants, the use of guidance for the humeral side warrants additional development and analysis. However, long-term studies remain necessary to determine the clinical outcomes and survivorship of such implants and whether the added cost and time of such modalities result in improved patient outcomes. In addition, the use of these technologies must be recognized as supplements to conducting TSA and not as a substitute for intraoperative decision making. Overall, the surgeon must be prepared to use the intraoperative findings to determine the final implant selection because many dynamic aspects of the functioning shoulder cannot be adequately measured with static imaging. As such, it remains the responsibility of the treating surgeon to remain adaptive to both emerging technologies and intraoperative experiences.

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