Reliability of a novel 3-dimensional computed tomography method for reverse shoulder arthroplasty postoperative evaluation

Gabriel Venne, DO, PhD [a,*], Michael Pickell, MD, MSc, FRCSC [b,c], Randy E. Ellis, PhD [b,c,d,e,f], Ryan T. Bicknell, MD, MSc, FRCSC [b,c,e]

[a] Department of Anatomy and Cell Biology, McGill University, Montréal, QC, Canada
[b] Department of Surgery, Queen's University, Kingston, ON, Canada
[c] Kinston General Hospital, Kingston, ON, Canada
[d] Department of Biomedical and Molecular Sciences, Queen's University, Kingston, ON, Canada
[e] Department of Mechanical and Materials Engineering, Queen's University, Kingston, ON, Canada
[f] School of Computing, Queen's University, Kingston, ON, Canada

Background: Long-term function and survival of reverse shoulder arthroplasties (RSAs) are reliant on component positioning and fixation. Conventional postoperative analysis is performed using plain radiographs or 2-dimensional (2D) computed tomography (CT) images. Although 3-dimensional (3D) CT would be preferred, its use is limited by metal artifacts. This study proposes a new 3D CT method for postoperative RSA evaluation and compares its interobserver reliability with conventional methods.

Materials and methods: Preoperative and postoperative CT scans, as well as postoperative radiographs, were obtained from 18 patients who underwent RSA implantation; the scapula, implant, and screws were reconstructed as 3D CT models. The postoperative 3D scapula and implant were imported into preoperative coordinates and matched to the preoperative scapula. Standardized scapula coordinates were defined, in which the glenoid baseplate version and inclination angle were measured. The percentage of screw volume in bone was measured from a Boolean intersection operation between the preoperative scapula and screw models. Four independent reviewers performed the measurements using 3D CT and conventional 2D methods. Intraclass correlation coefficients (ICCs) were used to compare the reliability of the methods.

Results: The 3D CT method showed excellent reliability (ICC > 0.75) in baseplate inclination (ICC = 0.92), version (ICC = 0.97), and screw volume in bone (ICC = 0.99). Conventional 2D methods demonstrated poor reliability (ICC < 0.4). For radiographs, inclination showed poor reliability (ICC = 0.09) and the screw percentage in bone showed fair reliability (ICC = 0.54). Version was not measured with plain radiographs. For 2D CT slice measurements, inclination showed poor reliability (ICC = 0.02), version showed excellent reliability (ICC = 0.81), and the screw percentage in bone showed poor reliability (ICC = 0.28).

Conclusion: The new 3D CT−based method for evaluating RSA glenoid implant positioning and screw volume in bone showed excellent reliability and overcame the metal-artifact limitation of postoperative CT and 3D CT reconstruction.

In joint arthroplasty, component placement and fixation are crucial to enable long-term procedure success and optimize patient outcomes. This has been shown to be particularly true in shoulder arthroplasty, especially reverse shoulder arthroplasty (RSA).[2,4,17,24] In RSA, high complication rates are often attributed to improper placement and fixation of components.[5,8,9,12,21,22] Postoperative evaluation is essential to understand complications related to component positioning. Although recent research has focused on developing computer-assisted surgery systems and on bone stock quality identification methods to better guide prosthetic placement, postoperative evaluation advancement has been limited.[1,7,17,19] Therefore, to improve the outcomes of RSA, better postoperative evaluation and measurement of baseplate and screw fixation are needed.

Conventional analysis of postoperative component placement is typically assessed using plain radiographs.[16,26] The accuracy of postoperative plain radiographs for assessing prosthetic placement has been discussed and brought into question.[20] Vidil et al[26] (2013) suggested that computed tomography (CT)
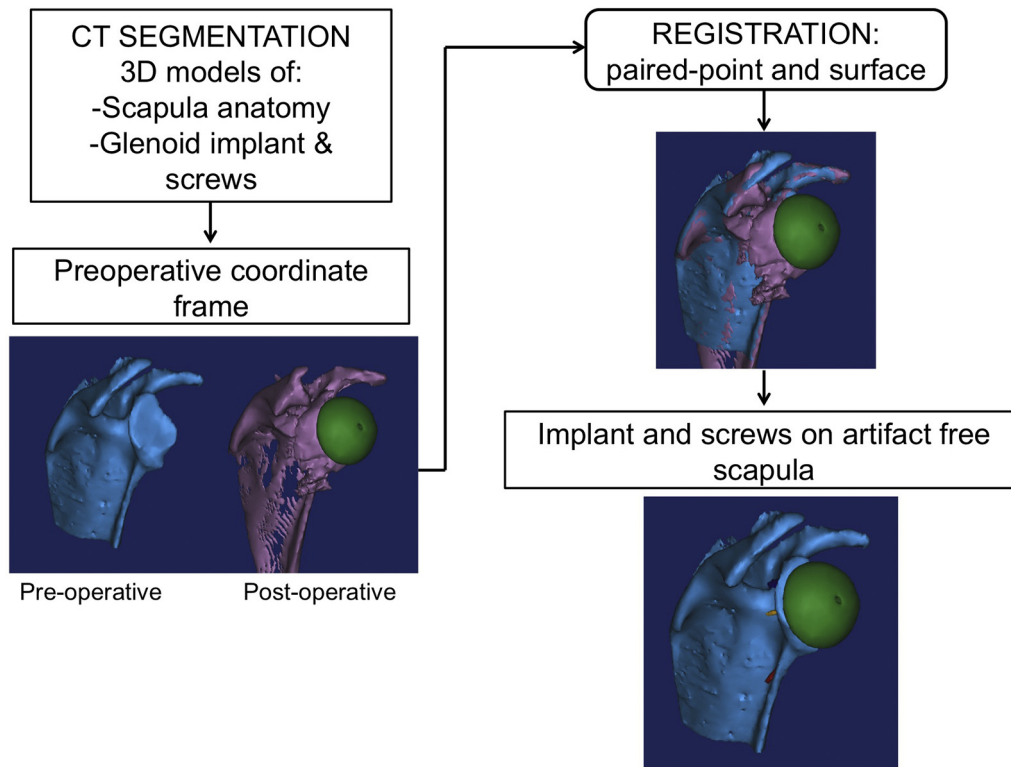
Figure 1 To perform the 3-dimensional (*3D*) model registration, preoperative and postoperative computed tomography (*CT*) scans were imported into medical imaging software. The scapula, glenoid implant, and screw were reconstructed as 3D models. The postoperative 3D scapula model and implant features were matched to the preoperative scapula model. The registrations were automatically propagated to the glenoid implant and screws, resulting in their placement on the artifact-free preoperative scapula model.

scanning is a more sensitive and reproducible tool to evaluate some postoperative placement features, but it remains a 2-dimensional (2D) representation; it is also limited because of metal artifacts.[14]

For preoperative planning and evaluation, recent literature has recommended 3-dimensional (3D) CT reconstruction over 2D CT or plain radiographs for a more reliable anatomic understanding and measurements, particularly when the anatomy is severely altered by osteoarthritis.[3,10,15,18] Postoperatively, the main limiting factor in using 3D CT reconstruction for evaluating implant placement has been metal artifacts caused by the implant.

An in vitro method using surface matching of the postoperative CT-based 3D model to the artifact-free preoperative CT-based 3D model to evaluate component placement has been previously described.[25,27] We postulated that a similar 3D CT reconstruction and registration technique could be developed for in vivo postoperative evaluation of glenoid baseplate implant and fixation in RSA patients.

The objectives of this study were to describe a new method for measuring RSA glenoid implant positioning as well as screw bone purchase using 3D CT−based reconstruction and to compare the interobserver reliability of this method with that of more conventional methods of postoperative baseplate and screw placement evaluation, including both 2D CT and plain radiography.

Materials and methods

Preoperative and postoperative CT scans, as well as plain radiographs, were obtained from 18 patients who had undergone RSA. Patients were randomly selected from the hospital archive system. Preoperative and postoperative CT scans were imported into commercially available medical imaging processing software (Mimics, version 15.0; Materialise, Leuven, Belgium). The patient

anatomy and prosthetics were automatically thresholded based on the gray-value histogram. The scapula, glenoid implant, and screws were then systematically reconstructed as 3D models.

Model registration

The postoperative 3D scapula model and implant features were imported into preoperative coordinates and matched to the preoperative scapula model. A first paired-point registration of the models was performed, followed by surface registration. For the paired-point registration, consistent points on the scapula were used. After the postoperative model and prosthetic were closely matched, surface matching was performed with a short distance threshold of 0.05 mm, at 10,000 iterations, until 100% of the subsample was reached. Only the scapula 3D models were used for the registration; the implant and screws were selected as moving objects, following the postoperative 3D model. The registrations were automatically propagated to the glenoid implant and screws, resulting in their placement on the artifact-free preoperative scapula model (Fig. 1).

Standardized scapula coordinates

Standardized scapula coordinates were required for baseplate spatial orientation measurements. To define scapula coordinates, a computer-assisted, custom-designed quadripod composed of 1 long axis with 2 orthogonal shorter axes was imported into the preoperative Mimics interface. The quadripod was registered to the preoperative scapula model using common landmarks: the center of the glenoid fossa and the trigonum scapulae (medial-lateral, z-axis), the superior and inferior glenoid tubercle (superior-inferior, y-axis), and the anterior-posterior axis (x-axis) as defined by the orthogonal-triad third axis[10,11,15] (Fig. 2).
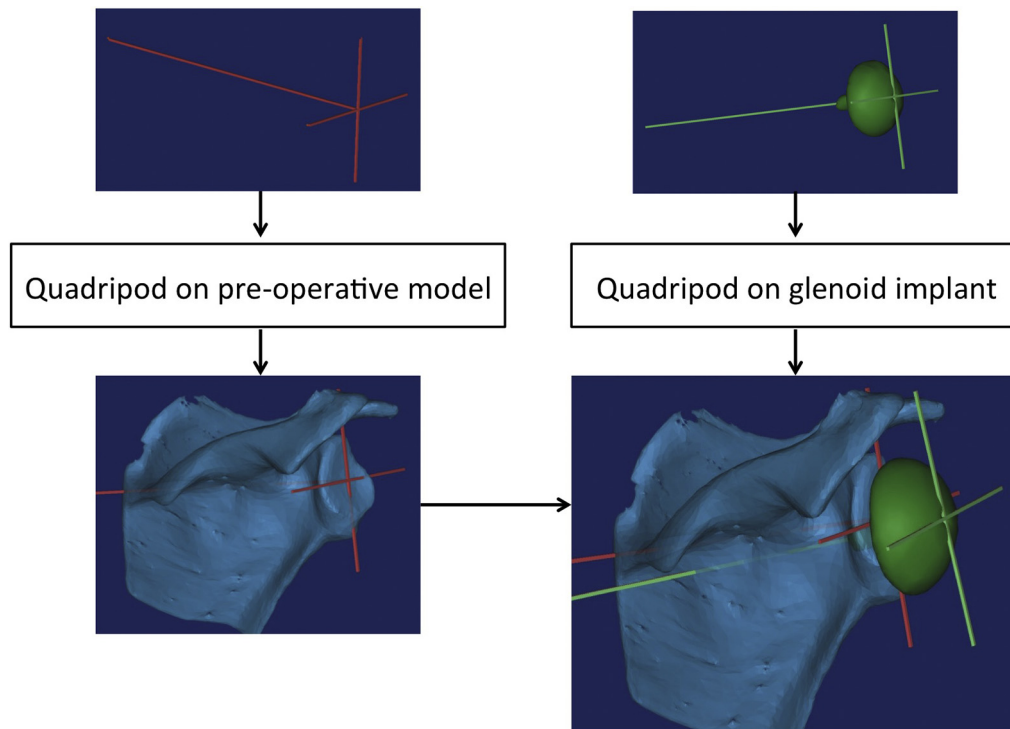
Figure 2 To establish scapula coordinates, a custom-designed quadripod was registered to the preoperative scapula model using common landmarks: the center of the glenoid fossa and the medial pole of the scapula where the scapular spine intersects (trigonum scapulae) (medial-lateral, z-axis), the superior and inferior glenoid tubercle (superior-inferior, y-axis), and the anterior-posterior axis (x-axis) that is defined by the orthogonal-triad third axis. To measure the implant position angles, a duplicate quadripod (*green*) was positioned along the central axis of the glenoid implant model along the central-peg axis.

Angle measurements

A duplicate quadripod was positioned along the central axis of the glenoid component model along the axis of the component's central peg (Fig. 2). The glenoid implant inclination and version were measured using a virtual protractor (MB-Ruler, version 5.2; MBSoftware Solutions, Baltimore, MD, USA). Inclination was measured between the central axis of the glenoid implant model and the transverse plane (x-/z-axes), and version was measured between the central axis of the glenoid implant model and the coronal plane (y-/z-axes) (Fig. 3).

Inferior screw volume in bone

It has been suggested that the inferior screw is the largest contributor to glenoid baseplate fixation by inducing point loading of RSA prosthetic components.[4] For this study, we modeled the quality of the screw position by measuring the 3D volume and location of the inferior screw within scapula bone.

For the percentage screw volume in bone, a Boolean intersection operation was performed between the preoperative scapula model and the inferior screw model. The volume of the intersection was compared with the volume of the original screw model, giving the bone-purchase percentage of the screw (Fig. 3).

Radiograph and CT-slice method

The same method was used for CT-slice and radiographic measurements. Cobb angles were used from the medical records software toolbox.

For postoperative inclination, a 90° Cobb angle was drawn from the trigonum of the scapula to the center of the central peg of the glenoid implant on coronal CT slices and anteroposterior radiographs. A second Cobb angle was drawn using the 90° line as a reference; the second line was placed from the most superior to the most inferior point on the glenoid implant.

The postoperative version angles could only be measured using CT slices because plain radiographs are ineffective in assessing glenoid version.[15] For the version of the glenoid, implant axial CT cuts were used. The same landmarks were used for placing the first Cobb angle. The second Cobb angle was drawn with respect to the most anterior to the most posterior point on the glenoid implant (Fig. 4). The screw percentage in bone was calculated from the screw length, collected with a distance-measuring tool in the software.

Data collection and statistical analysis

For testing of the interobserver reliability of the 3 methods—conventional plain radiographs and 2D CT, as well as the new 3D CT—based method—baseplate inclination and version and inferior screw bone purchase were measured by 4 qualified independent observers: an orthopedic surgeon, an anatomist, an experienced computer-assisted surgery research assistant, and a computer-science student.

The interobserver reliability was tested using the intraclass correlation coefficient [ICC (2)] of Shrout and Fleiss,[23] whereby measurements were made by the same observer and the observers were sampled from a population of observers. Baseplate inclination and version and the percentage of the inferior screw in bone were measured using 3 different methods: conventional plain radiographs, 2D CT, and the new 3D CT—based method. All measurements were individually performed on each of the 16 data sets by the 4 independent reviewers. A reliability score below 0.40 was
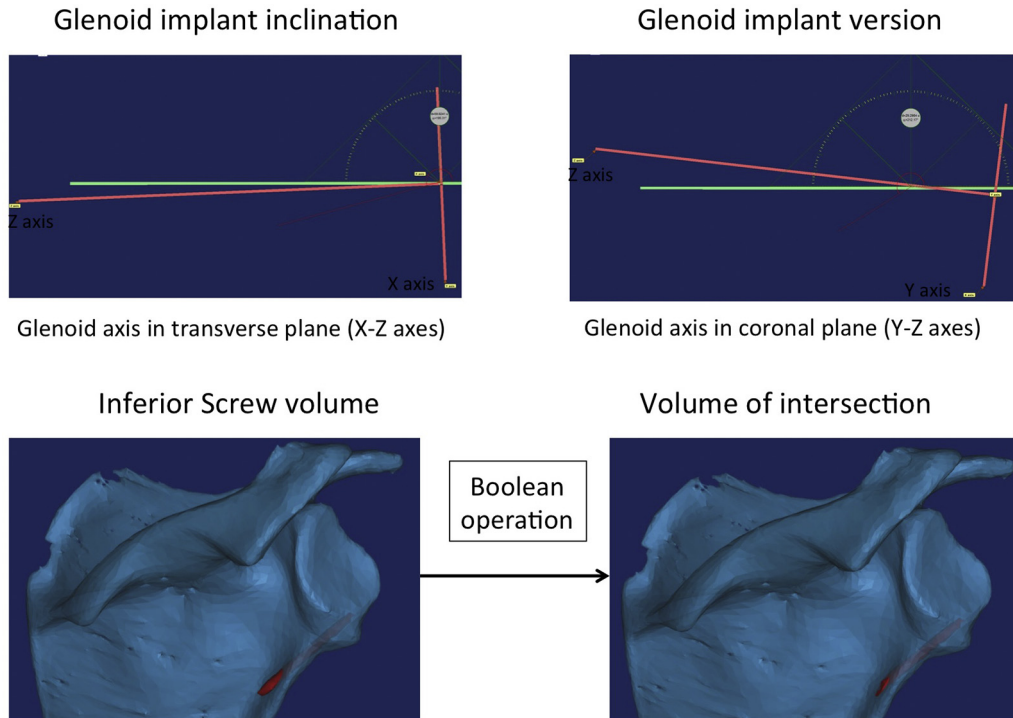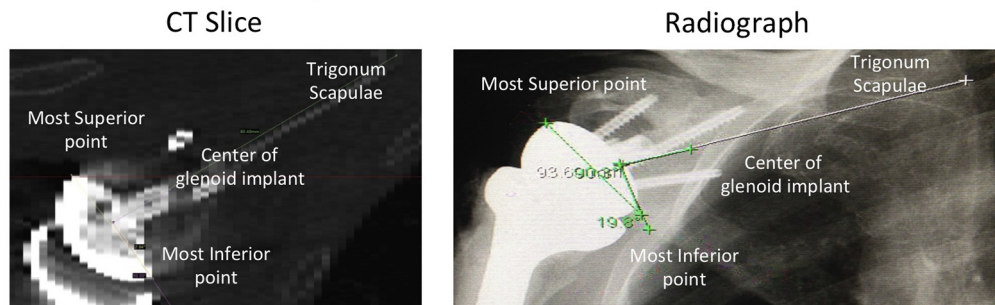
Glenoid implant inclination

Glenoid axis in transverse plane (X-Z axes)

Glenoid implant version

Glenoid axis in coronal plane (Y-Z axes)

Inferior Screw volume

Boolean operation →

Volume of intersection

Figure 3 To measure the glenoid implant inclination and version, a virtual protractor was used. Inclination was measured between the central axis of the glenoid implant model and the transverse plane (x-/z-axes), and version was measured between the central axis of the glenoid implant model and the coronal plane (y-/z-axes). To measure the percentage of the inferior screw volume in bone, a Boolean intersection operation was performed between the preoperative scapula model and the inferior screw model. The volume of the intersection was compared with the volume of the original screw model, giving the bone-purchase percentage of the screw.

Inclination: Cobb angle

CT Slice

Radiograph

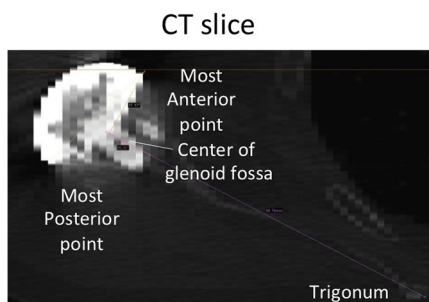# Version: on CT slices only

CT slice

Figure 4 For conventional methods, to determine postoperative inclination, a 90° Cobb angle was drawn from the trigonum of the scapula to the center of the central peg of the glenoid implant. A second Cobb angle was drawn using the 90° line as a reference; the second line was placed from the most superior to the most inferior point on the glenoid implant. The postoperative version angles could only be measured using computed tomography (CT) slices because plain radiographs are ineffective in assessing glenoid version. For the version of the glenoid implant, the same landmarks were used for placing the first Cobb angle. The second Cobb angle was drawn with respect to the most anterior to the most posterior point on the glenoid implant.

Table I
Overall mean of average absolute deviation of measures taken by 4 independent observers for each method

Measure	Radiographs	CT slices	Volumetric CT
Inclination, °	7.3	7.9	1.4
Version, °	NA	2.8	1.2
Volume of inferior screw in bone, %	5.3	15.3	1.4

CT, computed tomography; *NA*, not applicable.
The average absolute deviation is reported to characterize the dispersion among measures.

Table II
Results of ICC κ values for each evaluated method

Measure	Radiographs	CT slices	Volumetric CT
Inclination	0.09	0.02	0.92
Version	NA	0.81	0.97
Volume of inferior screw in bone	0.54	0.28	0.99

ICC, intraclass correlation coefficient; *CT*, computed tomography; *NA*, not applicable.
A reliability score below 0.40 was considered poor; between 0.41 and 0.59, fair; between 0.60 and 0.74, good; and between 0.75 and 1.00, excellent.

considered poor; between 0.41 and 0.59, fair; between 0.60 and 0.74, good; and between 0.75 and 1.00, excellent.[6] The overall mean of the average absolute deviation was reported to characterize the general dispersion among measures taken by the independent observers for each patient.

Results

The average absolute deviation is reported in Table I to characterize the dispersion among measures, and the results of ICC κ values for each evaluated method are reported in Table II. For the plain radiographic measures, the average deviation from preoperatively to postoperatively was 7.3° for inclination and 5.3% for the inferior screw volume–in–bone percentage. Reliability was poor for the angle of inclination (ICC = 0.09) and fair for the percentage of the inferior screw in bone (ICC = 0.54). The angle of version was not measured with plain radiographs.

For 2D CT-slice measurements, the average deviation from preoperatively to postoperatively was 7.6° for inclination, 2.8° for version, and 15.3% for the inferior screw volume–in–bone percentage. Reliability was poor for the angle of inclination (ICC = 0.02), excellent for the angle of version (ICC = 0.81), and poor for the percentage of the inferior screw in bone (ICC = 0.28).

For the 3D registration method, the average deviation from preoperatively to postoperatively was 1.4° for inclination, 1.2° for version, and 1.4% for the inferior screw volume–in–bone percentage. Reliability was excellent for the angle of inclination (ICC = 0.92), excellent for the angle of version (ICC = 0.97), and excellent for the percentage of the inferior screw in bone (ICC = 0.99).

Discussion

In RSA, component positioning is of paramount importance to optimize outcomes, avoid complications, and help ensure longevity.[2,4,18,25] Conventional evaluation methods for postoperative RSA implant and screw placement have historically been based on 2D imaging.[17,27] However, the reliability and accuracy of assessing component positioning using 2D plain radiography have been questioned.[21] Our results suggest that assessing implant position using 2D conventional methods is unreliable and that the new 3D CT evaluation showed excellent intraobserver reliability.

Although 3D CT reconstruction has been suggested to be more reliable for assessing shoulder anatomy,[3,11,16,19] 3D CT has thus far been limited to preoperative evaluation. Previously, postoperative evaluation has been limited by metal artifacts and distortion created by the components that compromise the accuracy of the postoperative imaging. Recent progress has been made in metal-artifact removal algorithms that have shown promising results. However, technical progress in improving the image acquisition process and reconstruction approaches is necessary before it is more widely applied.[13,14,28] The results of the new method demonstrated in this study, using 3D CT registration of postoperative to preoperative anatomy for evaluating RSA glenoid implant and screw positioning, suggest that it is possible to overcome the metal-artifact limitation of a 3D CT postoperative evaluation.

The observers involved with this study were selected from different fields and included an orthopedic surgeon, an anatomist, an experienced computer-assisted surgery research assistant, and a computer-science student. Although every observer was trained according to the same protocol, the difference in fields of practice could have compromised the reliability of conventional measurements and is therefore a limitation of this study. However, the results could suggest that the 3D CT–based method was easy to learn and to apply in practice and that it is not technically challenging or experience dependent.

Although preoperative radiographs are routinely acquired and multiple studies have demonstrated that CT and 3D reconstruction are more adequate tools to evaluate postoperative placement features, obtaining preoperative and postoperative CT scans is increasingly a standard practice in RSA surgery but is not a common practice in every institution. Therefore, another limitation of this study is the applicability of the described technique, which involves the feasibility to perform a postoperative CT scan. This exposes the patient to radiation and potentially adds further cost to patient care. This technique is not proposed to be performed for routine follow-up in every clinical situation, especially not for the typical postoperative patient. However, this technique has important benefits and may find an application in 2 situations. The first situation would be for evaluation of patients who are not doing as well as might be expected. This may include patients with unexplained pain, instability, or lack of functional improvement, particularly those for whom the surgeon is contemplating performing revision arthroplasty. These are all situations in which a postoperative CT scan would often be performed, and this technique could add some benefits to a routine CT scan. The second situation would be for research purposes in which a detailed evaluation of implant positioning may be beneficial. Therefore, although this technique may not find an application for the typical patient or be used on a routine basis, we feel this technique offers some benefits to surgeons in the aforementioned situations.

Furthermore, this method is translatable to postoperative evaluation of other procedures that are currently limited by imaging metal artifacts. More work could be performed to increase the number of patients examined to assess the reliability of this method and to adapt this method to other joints and procedures.

Conclusion

A new 3D CT–based method for evaluating RSA glenoid implant positioning and screw volume in bone has been developed. This method overcame the metal-artifact limitation of postoperative 3D CT reconstruction. It showed excellent intraobserver reliability compared with more conventional 2D methods. Future directions could include large-scale validation and application to postoperative imaging evaluation of other procedures currently limited by metal artifacts.

Disclaimer

References

1. Berhouet J, Gulotta LV, Dines DM, Craig E, Warren RF, Choi D, et al. Preoperative planning for accurate glenoid component positioning in reverse shoulder arthroplasty. Orthop Traumatol Surg Res 2017;103:407–13. https://doi.org/10.1016/j.otsr.2016.12.019.
2. Briem D, Ruecker AH, Neumann J, Gebauer M, Kendoff D, Gehrke T, et al. 3D fluoroscopic navigated reaming of the glenoid for total shoulder arthroplasty (TSA). Comput Aided Surg 2011;16:93–9. https://doi.org/10.3109/10929088.2010.546076.
3. 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 Shoulder Elbow Surg 2011;20:577–83. https://doi.org/10.1016/j.jse.2010.11.003.
4. Chebli C, Huber P, Watling J, Bertelsen A, Bicknell RT, Matsen 3rd F. Factors affecting fixation of the glenoid component of a reverse total shoulder prothesis. J Shoulder Elbow Surg 2008;17:323–7. https://doi.org/10.1016/j.jse.2007.07.015.
5. 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.
6. Cicchetti DV. Guidelines, criteria, and rules of thumb for evaluating normed and standardized assessment instruments in psychology. Psychol Assess 1994;6:284–90.
7. Daalder M, Gabriel V, Varun S, Michael R, Timothy B, Ryan TB. Trabecular bone density distribution in the scapula relevant to reverse shoulder arthroplasty. JSES Open Access 2018;2:174–81. https://doi.org/10.1016/j.jses.2018.06.002.
8. Farshad M, Gerber C. Reverse total shoulder arthroplasty-from the most to the least common complication. Int Orthop 2010;34:1075–82. https://doi.org/10.1007/s00264-010-1125-2.
9. Favre P, Sussmann PS, Gerber C. The effect of component positioning on intrinsic stability of the reverse shoulder arthroplasty. J Shoulder Elbow Surg 2010;19:550–6. https://doi.org/10.1016/j.jse.2009.11.044.
10. Frankle MA, Teramoto A, Luo ZP, Levy JC, Pupello D. Glenoid morphology in reverse shoulder arthroplasty: classification and surgical implications. J Shoulder Elbow Surg 2009;18:874–85. https://doi.org/10.1016/j.jse.2009.02.013.
11. 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 Shoulder Elbow Surg 2011;20:234–44. https://doi.org/10.1016/j.jse.2010.05.024.
12. Gavaskar AS, Vijayraj K, Subramanian SD. Intraoperative CT navigation for glenoid component fixation in reverse shoulder arthroplasty. Indian J 2013;47:104–6. https://doi.org/10.4103/0019-5413.106935.
13. Gjesteby L, De Man B, Jin Y, Paganetti H, Verburg J, Giantsoudi D, et al. Metal artifact reduction in CT: where are we after four decades? IEEE Access 2016;4:5826–49. https://doi.org/10.1109/ACCESS.2016.2608621.
14. Hakim A, Slotboom J, Lieger O, Schlittler F, Giger R, Michel C, et al. Clinical evaluation of the iterative metal artefact reduction algorithm for post-operative CT examination after maxillofacial surgery. Dentomaxillofac Radiol 2017;46:20160355. https://doi.org/10.1259/dmfr.20160355.
15. Hoenecke Jr HR, Hermida JC, Flores-Hernandez C, D'Lima DD. Accuracy of CT-based measurements of glenoid version for total shoulder arthroplasty. J Shoulder Elbow Surg 2010;19:166–71. https://doi.org/10.1016/j.jse.2009.08.009.
16. Kadum B, Mukka S, Englund E, Sayed-Noor A, Sjödén G. Clinical and radiological outcome of the Total Evolutive Shoulder System (TESS) reverse shoulder arthroplasty: a prospective comparative non-randomised study. Int Orthop 2014;38:1001–6. https://doi.org/10.1007/s00264-013-2277-7.
17. Kircher J, Wiedemann M, Magosch P, Lichtenberg S, Habermeyer P. Improved accuracy of glenoid positioning in total shoulder arthroplasty with intraoperative navigation: a prospective-randomized clinical study. J Shoulder Elbow Surg 2009;18:515–20. https://doi.org/10.1016/j.jse.2009.03.014.
18. Kubicka AM, Stefaniak J, Lubiatowski P, Długosz J, Dzianach M, Redman M, et al. Reliability of measurements performed on two dimensional and three dimensional computed tomography in glenoid assessment for instability. Int Orthop 2016;40:2581–8. https://doi.org/10.1007/s00264-016-3253-9.
19. Mansat P, Bonnevialle N. Morphology of the normal and arthritic glenoid. Eur J Orthop Surg Traumatol 2013;23:287–99. https://doi.org/10.1007/s00590-012-1115-8.
20. Namdari S, Hsu JE, Barron M, Huffman GR, Glaser D. Immediate postoperative radiographs after shoulder arthroplasty are often poor quality and do not alter care shoulder. Clin Orthop Relat Res 2013;471:1257–62. https://doi.org/10.1007/s11999-012-2551-9.
21. Nyffeler RW, Werner CML, Gerber C. Biomechanical relevance of glenoid component positioning in the reverse Delta III total shoulder prosthesis. J Shoulder Elbow Surg 2005;14:524–8. https://doi.org/10.1016/j.jse.2004.09.010.
22. Ortmaier R, Resch H, Matis N, Blocher M, Auffarth A, Mayer M, et al. Reverse shoulder arthroplasty in revision of failed shoulder arthroplasty—outcome and follow-up. Int Orthop 2013;37:67–75. https://doi.org/10.1007/s00264-012-1742-z.
23. Shrout PE, Fleiss JL. Intraclass correlations: uses in assessing rater reliability. Psychol Bull 1979;86:420–8.
24. Stephens BF, Hebert CT, Azar FM, Mihalko WM, Throckmorton TW. Optimal baseplate rotational alignment for locking-screw fixation in reverse total shoulder arthroplasty: a three-dimensional computer-aided design study. J Shoulder Elbow Surg 2015;24:1367–71. https://doi.org/10.1016/j.jse.2015.01.012.
25. Venne G, Rasquinha BJ, Pichora D, Ellis RE, Bicknell R. Comparing conventional and computer-assisted surgery baseplate and screw placement in reverse shoulder arthroplasty. J Shoulder Elbow Surg 2015;24:1112–9. https://doi.org/10.1016/j.jse.2014.10.012.
26. Vidil A, Valenti P, Guichoux F, Barthas JH. CT scan evaluation of glenoid component fixation: a prospective study of 27 minimally cemented shoulder arthroplasties. Eur J Orthop Surg Traumatol 2013;23:521–5. https://doi.org/10.1007/s00590-012-1126-5.
27. Walch G, Vezeridis 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 Shoulder Elbow Surg 2015;24:302–9. https://doi.org/10.1016/j.jse.2014.05.029.
28. Whitmarsh T, Treece GM, Gee AH, Poole KES. An exploratory study into measuring the cortical bone thickness from CT in the presence of metal implants. Int J Comput Assist Radiol Surg 2017;12:2079–86. https://doi.org/10.1007/s11548-017-1539-z.