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Intraoperative navigation and preoperative templating software are associated with increased glenoid baseplate screw length and use of augmented baseplates in reverse total shoulder arthroplasty

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A R T I C L E I N F O

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Level of evidence: Level III; Retrospective Cohort Comparison; Treatment Study

Background: Preoperative templating software and intraoperative navigation have the potential to impact baseplate augmentation utilization and increase screw length for baseplate fixation in reverse total shoulder arthroplasty (rTSA). We aimed to assess their impact on the (1) baseplate screw length, (2) number of screws used, and (3) frequency of augmented baseplate use in navigated rTSA.

Methods: We compared 51 patients who underwent navigated rTSA with 63 controls who underwent conventional rTSA at a single institution. Primary outcomes included the screw length, composite screw length, number of screws used, percentage of patients in whom 2 screws in total were used, and use of augmented baseplates.

Results: Navigation resulted in the use of significantly longer individual screws (36.7 mm vs. 30 mm, $P < .0001$), greater composite screw length (84 mm vs. 76 mm, $P = .048$), and fewer screws (2.5 ± 0.7 vs. 2.8 ± 1, $P = .047$), as well as an increased frequency of using 2 screws in total (35 of 51 patients [68.6%] vs. 32 of 63 controls [50.8%], $P = .047$). Preoperative templating resulted in more frequent augmented baseplate utilization (76.5% vs. 19.1%, $P < .0001$).

Conclusion: The difference in the screw length, number of screws used, and augmented baseplate use demonstrates the evolving role that computer navigation and preoperative templating play in surgical planning and the intraoperative technique for rTSA.

Reverse total shoulder arthroplasty (rTSA) has become a mainstay of treatment for patients with rotator cuff arthropathy and is becoming more common for some patients with glenohumeral arthritis. The indications for rTSA are still evolving and are continuing to expand. In general, most available rTSA designs include a glenoid baseplate that is secured by a central peg, keel, or screw in the glenoid vault, with a variety of screw arrangement designs for supplemental fixation into scapular bony corridors. These supplemental screws can be locking or nonlocking and variable or fixed angle. Secure fixation of the baseplate is paramount to prevent glenoid component loosening.[30] Inadequate initial glenoid baseplate fixation has been shown to lead to early glenoid loosening from micromotion and a lack of osseous integration.[7] Rates of baseplate loosening from 1.2 to 5% have been reported.[4,30] Secure fixation of the baseplate to the glenoid has been attributed to a number of factors including bone quality, number of screws, screw length, arrangement and angle of divergence of screws, and central peg length. Numerous studies have attempted to examine the impact of these factors on fixation, with mixed results.[5,10,11,13-17] However, it appears that, in general, longer screws that achieve bicortical purchase in dense bone provide the best fixation.[11,14,17]

Computer-assisted intraoperative navigation and preoperative planning software applications in rTSA have only recently been described in the orthopedic literature because of the relative infancy of the technology.[21,22,27] Patient-specific instrumentation and 3-dimensional (3D) imaging and templating technologies improve the accuracy of glenoid component placement in accordance with a preoperative plan.[1,3,12,20,26,27] In addition, 3D templating may

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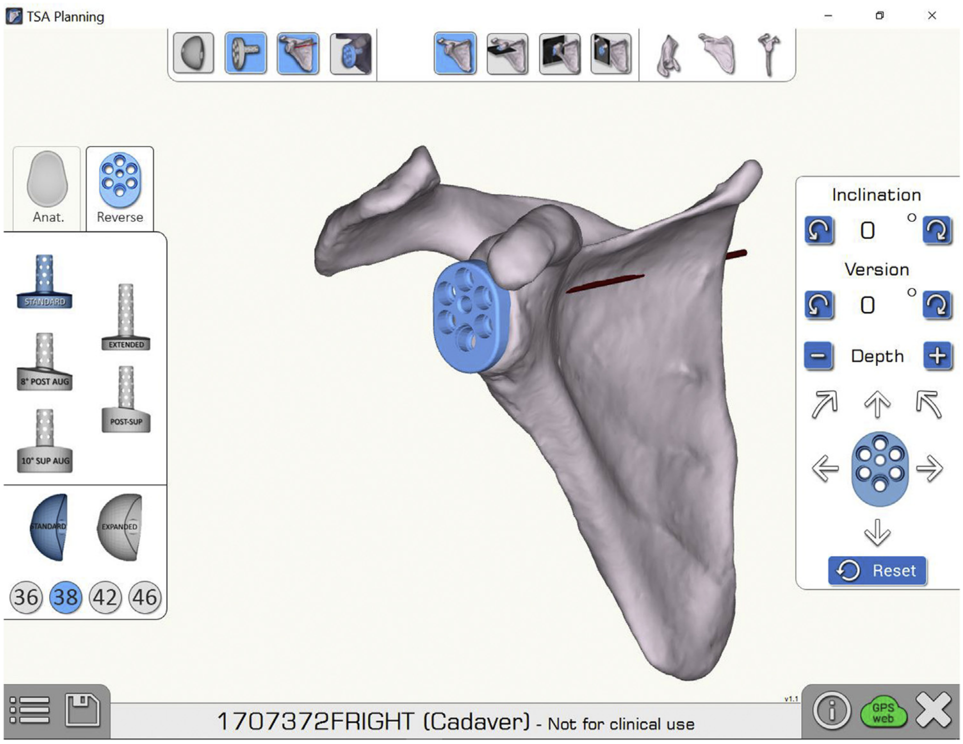

Figure 1 The Equinoxe Planning App preoperative planning software is shown, demonstrating the ability to virtually construct the ideal glenoid baseplate type and position for each patient's scapular anatomy. *Post Aug*, posterior augment; *Post-Sup*, posterosuperior augment; *10° Sup Aug*, 10° superior augment; *Anat.*, anatomic baseplate.

increase the accuracy of screw placement relative to the preoperative plan.[25] To our knowledge, only 1 previous study has evaluated the difference in achievable baseplate screw length between navigated and conventional rTSA.[19]

We sought to evaluate the impact of preoperative templating software and intraoperative navigation on baseplate component specifications by comparing the (1) average screw length, (2) composite screw length (ie, combined length of all screws), (3) average number of screws used, (4) percentage of patients in whom 2 screws in total were used, and (5) frequency of augmented baseplate use. Operative time was examined as a secondary variable. We hypothesized that intraoperative navigation assistance would allow the primary surgeons to use longer and fewer screws to achieve what they deemed secure baseplate fixation, as compared with secure baseplate fixation when intraoperative navigation assistance was not used.

Materials and methods

Surgical technique

All patients underwent rTSA with the Exactech Equinoxe system (Exactech, Gainesville, FL, USA), which has a design that uses a medialized glenoid and lateralized humerus.[24] Augmented baseplates were available for use throughout the study period; these included baseplates with a superior, posterior, or superior-posterior augmentation, a small baseplate size, or an extended central peg. All standard-sized baseplates (including augmented baseplates) have 6 screw hole options (superior, inferior, superior-anterior, superior-posterior, inferior-anterior, and inferior-posterior), whereas the small baseplate has 4 screw hole options (superior, inferior, inferior-anterior, and inferior-posterior).

In the large majority of non-navigated cases, the decision to use a standard or augmented glenoid baseplate component was made using a preoperative computed tomography (CT) scan (if available) combined with an intraoperative assessment of glenoid morphology. The Equinoxe Planning App preoperative planning software and ExactechGPS Total Shoulder Application intraoperative navigation system (Exactech) were used for all navigated cases (Fig. 1). This technology offers the surgeon a 3D rendered model of the patient's scapula, created from the preoperative CT scan. The software then allows the surgeon to place sized-to-scale renderings of all baseplate options onto the scapula model and make adjustments in baseplate positioning in all planes in 1-mm and 1° increments. The presurgical plan is saved and uploaded to the intraoperative navigation system prior to surgery. Regardless of the use of navigation, the baseplate-glenoid interface was inspected intraoperatively to ensure a flush fit.

A standard deltopectoral approach was performed with a 1- to 2-cm cranial extension of the incision for coracoid exposure in patients who underwent navigated rTSA. Navigation was not available for placement of the humeral component. Therefore, humeral head osteotomy, reaming, broaching, and placement of the humeral component were performed in similar fashions in both groups.

In the non-navigated group, the baseplate central peg positioning and reaming of the glenoid were performed using a standard technique.[6] When navigation was used, the superior and inferior aspects of the coracoid were dissected with cautery to allow for placement of a tracker that corresponded with the intraoperative navigation screen. The tracker was then placed on the superior coracoid with 2 self-tapping screws. It was linked to the intraoperative monitor, and several points on the glenoid and coracoid were registered using a stylus. An additional tracker that corresponded with the intraoperative navigation screen was attached to the base of the ExactechGPS reamer handle, and the corresponding drills and reamers for each step in the procedure were attached to this reamer handle. Locating the center point of

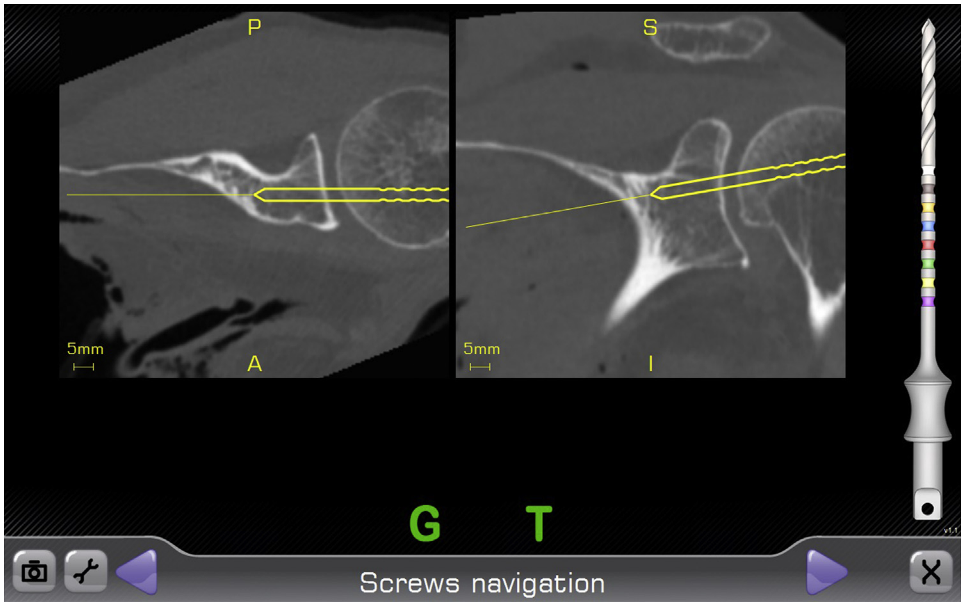

Figure 2 The ExactechGPS navigation screen is shown, demonstrating the real-time, intraoperative drill bit trajectory in relation to the patient's scapula, rendered from a preoperative computed tomography scan.

the glenoid, drilling of the center peg hole, and glenoid reaming were carried out under navigation, according to the preoperative plan. The selected baseplate component was then impacted onto the glenoid.

The variable-angle compression screws were drilled using the adjustable-angle drill guide with a standard 3.2-mm drill bit for the non-navigated cases and with an ExactechGPS-specific drill bit for the navigated cases. The navigation screen displays the trajectory of the drill bit in relation to coronal and sagittal CT images of the bony scapula in real time, which allows the surgeon to aim in a manner that will access the longest bony corridor provided by each patient's unique glenoid and scapular anatomy (Fig. 2). Pre-drill aiming also allows the surgeon to avoid areas of the scapula that could endanger soft-tissue structures, such as the suprascapular notch.[9] The compression screws are available in sizes from 18 to 46 mm in 4-mm increments. Both the standard and ExactechGPS drill bits have color-coded, etched markings on them that correspond to these increments. Regardless of navigation status, the hole depth was gauged by noting the drill bit depth marking that was flush with the drill guide at the time of cortical breakthrough. Cortical breakthrough was determined using tactile feel regardless of navigation status. However, the navigation technology also provided real-time, intraoperative animation on the navigation screen that allowed the surgeon to visualize the drill bit nearing the far cortex and the cortical breakthrough event.

Superior and inferior screw positions on the baseplate were used first in all cases. The decision to place additional screws was made intraoperatively, based on the surgeon's tactile assessment of purchase of the first 2 screws. Essentially, the quality of "bite" of the first 2 screws determined whether additional screws were used. Locking caps were then placed over each screw head, and the glenoid component was completed by placing the glenosphere according to the technique guide.[6] The humeral polyethylene component size was chosen based on soft-tissue tensioning; the humeral component was then secured following the technique guide. The wound was closed in standard layered fashion.

Study design

This study was a case-control, retrospective review of 114 rTSAs performed in 108 patients at a single institution by 1 of 2 fellowship-trained, board-certified, experienced primary surgeons. The non-navigated study group consisted of 63 surgical procedures performed from January 2018 to July 2019. Computer-assisted intraoperative navigation technology became available at our institution in October 2018. The navigated study group consisted of 51 surgical procedures performed from October 2018 to July 2019. Since navigation technology became available at our institution, 6 patients have been prevented from undergoing a navigated rTSA. This was because of either a lack of preoperative CT scans or anatomic factors that were not conducive to coracoid tracker placement, such as a small coracoid size or previous coracoid fracture. These patients were included in the non-navigated group. Preoperative surgical indications included rotator cuff arthropathy, fracture malunion, and complications from prior humeral hardware, as well as 1 chronic shoulder dislocation (listed as "other") (Table I). The exclusion criteria included any prior major glenoid reconstruction or instrumentation, revision of prior rTSA, or conversion to rTSA.

A review of the electronic medical record was performed to obtain patient age, sex, height, weight, and body mass index (BMI). A review of the operative notes was performed to record laterality of surgery, baseplate type used, number of screws used, individual screw lengths, and length of procedure. Each patient's preoperative CT scan, if available, was then used to describe the patient's glenoid anatomy. Glenoid retroversion was first measured from CT images using the technique described by Friedman et al[8] and Rouleau et al.[23] The posterior subluxation index was calculated from CT scans as well, using the method described by Walch et al.[27] Each glenoid was then classified using the modified Walch classification.[2] There were 14 patients in the non-navigated group for whom glenoid morphology could not be evaluated as they did not undergo CT scans prior to surgery. For patients with CT scans in both groups,

Table I
Descriptive statistics of study population

Variable	Frequency (%)
rTSA	
Non-navigated	63 (55.3)
Navigated	51 (44.7)
Surgery indication	
Rotator cuff arthropathy	106 (93)
Fracture	3 (2.6)
Hardware complication	4 (3.5)
Other	1 (0.9)
Walch classification	
A1	47 (47.5)
A2	12 (12.1)
B1	8 (8.1)
B2	9 (9.1)
B3	7 (7.1)
C	1 (1.0)
D	15 (15.2)
Baseplate type used	
Standard	63 (55.3)
Extended cage	1 (0.9)
Posterior augmentation	16 (14.0)
Superior augmentation	17 (14.9)
Posterior-superior augmentation	16 (14.0)
Small	1 (0.9)
Total No. of screws used	
2	67 (59)
3	25 (21.9)
4	18 (15.8)
5	4 (3.5)

rTSA, reverse total shoulder arthroplasty.

the complexity of glenoid morphology was assessed by comparing the frequency of glenoids classified as Walch type A and those classified as non−Walch type A (Walch type B, C, or D). The composite screw length was calculated by summing all screw lengths. This measure was used as a means to quantify the total screw fixation length independent of the number of screws used.

Statistical analysis

SAS software (version 9.4; SAS Institute, Cary, NC, USA) was used for statistical analysis. Sample characteristics were described using descriptive statistics. Frequencies and percentages were used to describe categorical variables. Means and standard deviations or medians and ranges were used to describe continuous variables. Bivariate analysis was performed for patient-specific variables and operative variables. We performed χ^2 tests for sex, laterality, Walch classification, surgeon, and baseplate type. Two-sample *t* tests were performed for age, posterior subluxation index, and operative time. We performed Wilcoxon rank sum tests for height, weight, BMI, glenoid retroversion, number of screws used, individual screw length, composite screw length, and frequency of 2 screws used in total. The significance level was set to $P < .05$ for all tests.

Results

Frequencies and percentages of categorical variables are provided in Table I. Bivariate comparisons of patient-specific variables are presented in Table II. The navigated and non-navigated groups showed statistically significant differences in median glenoid retroversion (4.1° [interquartile range, 47.1°] vs. 8.4° [interquartile range, 46.7°], $P = .016$) and the mean posterior subluxation index (0.50 ± 0.1 vs. 0.57 ± 0.1, $P = .002$). The 2 groups did not have statistically different glenoid morphology by the Walch classification ($P = .743$). Moreover, there were no other statistically significant differences between the groups for patient-specific variables, including age, height, weight, BMI, sex, and laterality.

Bivariate comparisons of the operative variables are presented in Table III. There was no significant difference in the frequency of procedures performed by surgeon 1 vs. surgeon 2 between the groups ($P = .380$). The average individual screw length was significantly higher in the navigated group (36.7 mm vs. 30 mm, $P < .0001$). The median composite screw length was also higher in the navigated group (84 mm vs. 76 mm, $P = .048$), despite the use of significantly fewer screws per case (2.5 ± 0.7 vs. 2.8 ± 1, $P = .047$). The frequency of using 2 screws in total was significantly higher in the navigated group (35 of 51 patients [68.6%] vs. 32 of 63 controls [50.8%], $P = .047$). The frequency of augmented baseplate use (39 [76.5%] vs. 12 [19.1%], $P < .0001$) and the operative time (98.6 ± 19.5 minutes vs. 85.8 ± 18.7 minutes, $P = .001$) were significantly higher in the navigated group.

Discussion

The patient-specific variables of the 2 study groups in this report were well matched with respect to age, sex, laterality, and BMI. A statistically significant difference of 4.3° of median glenoid retroversion (8.4° vs. 4.1°, $P = .017$) was found in the non-navigated group. However, both groups had median retroversion within the normal range for anatomic glenoid retroversion (1°-9°), and the 2 study groups did not have statistically different glenoid morphology by the modified Walch classification ($P = .744$).[18] The modified Walch classification was used to characterize glenoid morphology because it is a well-known CT-based system that was most translatable when assessing the glenoid using the 3D preoperative templating software.

A longer individual screw length was attained using intraoperative navigation technology (36.7 mm vs. 30 mm). A longer screw length (36 vs. 18 mm), specifically in the anterior and inferior screw positions, has been associated with biomechanically stronger initial fixation, but the number of screws (2 vs. 4) and angle of screw divergence (0° vs. 27°) have not.[17] The finding of an improved screw length with navigation technology is in concordance with the results of Nashikkar et al.[19] However, the improvement was isolated to the anterior and posterior screws with a much shorter maximum screw length (20 mm) in comparison to our study. This difference is likely due to surgeon-dependent variation in preoperative goals for screw position and length. Obtaining the maximum screw length may be seen as having secondary importance to placing screws into the areas of highest bone density in the scapula, particularly the base of the coracoid, the scapular pillar, and the scapular spine.[11] Nashikkar et al routinely placed screws in at least 4 of the 5 screw holes with maximal screw divergence, possibly leading to a shorter maximum attainable length for each screw.

In contrast, the surgeons involved in this study routinely look to minimize the number of screws used. Two screws were placed in the inferior and superior positions, at a minimum. On the basis of tactile assessment of screw purchase, or bite, the surgeon decided whether to add a third or fourth screw. Fewer screws were used on average with the use of navigation technology, with 2 screws in total used more frequently. The increased frequency of the use of 2 screws in total is not biomechanical evidence of improved fixation but does reflect increased surgeon confidence in the level of fixation intraoperatively. Improved screw length and visual confirmation of intraosseous placement of the screws using the navigation technology likely contributed to this increased confidence. A longer individual screw length has been shown to provide significantly better baseplate fixation after cyclic loading, regardless of the number of screws used.[22] The post hoc planning in this study alleviates potential concerns that the surgeons used fewer screws for the sole purpose of obtaining significant results. We cannot draw

Table II
Bivariate comparison of patient-specific variables in non-navigated and navigated rTSA groups

	Non-navigated rTSA (n = 63)		Navigated rTSA (n = 51)		*P* value
	Mean ± SD or frequency (%)	Median (interquartile range)	Mean ± SD or frequency (%)	Median (interquartile range)	
Age, yr	72.1 ± 7.9		36 (70.6)		.6733
Height, cm		165.1 (48.2)	15 (29.4)	167.6 (33)	.3559
Weight, kg		87.5 (100)	71.5 ± 7.9	81.6 (75.8)	.9183
BMI, kg/m^2		30.8 (31.6)		29.2 (22.9)	.7442
Sex					.2634
Male	24 (52.2)		22 (47.8)		
Female	39 (62.9)		23 (37.1)		
Laterality					.1576
Right shoulder	38 (61.3)		24 (38.7)		
Left shoulder	25 (48.1)		27 (51.9)		
Glenoid morphology					
Glenoid retroversion, °		8.4 (46.7)		4.1 (47.1)	.0166*
Posterior subluxation index	0.57 ± 0.1		0.50 ± 0.1		.0020*
Walch classification					.7437
A	30 (50.9)		29 (49.2)		
B, C, or D	19 (47.5)		21 (52.5)		

rTSA, reverse total shoulder arthroplasty; *SD*, standard deviation; *BMI*, body mass index.
* Statistically significant ($P < .05$).

Table III
Bivariate comparison of operative variables in non-navigated and navigated rTSA groups

	Non-navigated rTSA		Navigated rTSA		*P* value
	Mean ± SD or frequency (%)	Median (range)	Mean ± SD or frequency (%)	Median (range)	
Surgeon					.3808
Surgeon 1	49 (77.8)		36 (70.6)		
Surgeon 2	14 (22.2)		15 (29.4)		
Baseplate screws					
No. of screws used	2.8 ± 1		2.5 ± 0.7		.0472*
Individual screw length, mm		30 (20)		36.7 (22)	<.0001*
Composite screw length, mm		76 (90)		84 (86)	.0481*
Frequency of 2 screws used in total	32 (50.8)		35 (68.6)		.0472*
Baseplate type					<.0001*
Standard	51 (81)		12 (23.5)		
Augmented	12 (19.1)		39 (76.5)		
Operative time, min	85.8 ± 18.7		98.6 ± 19.5		.0006*

rTSA, reverse total shoulder arthroplasty; *SD*, standard deviation.
* Statistically significant ($P < .05$).

any biomechanical conclusions based on these data, but these results do reflect a significant change in practice at our institution because of intraoperative navigation.

The relationship between the number of screws used and biomechanical strength in baseplate fixation is unclear, with some evidence supporting the use of more screws and some refuting their use.[5,10,13-15] The complex interplay between the implant design and the importance of screw trajectory to biomechanical strength makes it difficult to fully evaluate the impact of using additional screws. Theoretically, using fewer screws might preserve scapular bone stock in case revision surgery is necessary in the future. Notably, the use of fewer screws in this study did not result in loss of the average composite screw length, with 8 mm of additional average composite screw length using navigation.

Unexpectedly, we found a drastic increase in augmented baseplate use from 19.1% to 76.5% ($P < .0001$) in the navigated group. Preoperative templating software has been shown to increase the awareness of glenoid bone loss and the need for augmented glenoid baseplates to achieve post-implantation version of 0°-10° of retroversion for anatomic total shoulder arthroplasty.[12] Even so, our use of augmentations in 76.5% of navigated shoulders is much greater than that in previous studies of rTSA and anatomic total shoulder arthroplasty.[1,12] The decision to use augmentation is left to surgeon discretion. True optimal post-implantation glenoid version in rTSA has yet to be defined, and long-term outcome studies are necessary to better define the indications for augmented baseplate use. A recent study by Parsons et al[21] detailed significant variation in the criteria for augmented baseplate utilization among 9 surgeons but found a uniform rate of overall utilization of augmentations, at 79%. The surgeons in our study attempt to implant the baseplate perpendicular to the Friedman line to achieve what is essentially neutral version. With this goal in mind, we attribute the drastic increase in the use of augmentation to the use of the 3D animated preoperative planning software. The software provides 3D feedback on the projected baseplate version relative to the Friedman line, possibly granting a better appreciation of glenoid morphology and final baseplate version. The use of this technology and augmented baseplates has been shown to allow for correction to neutral version in 63% of cases.[21] The surgeons in our study anecdotally found that the use of augmentation allowed them to rely less on reaming to achieve their desired version. However, the amount of required reaming and the accuracy with which the implanted baseplate's version matched the preoperative plan were not assessed. Multiple studies have confirmed that simply using 3D technology platforms to virtually implant glenoids preoperatively is helpful in improving surgeon accuracy in baseplate positioning intraoperatively.[1,3,12,28,29]

The use of navigation increased the operative time by 12.8 minutes (98.6 ± 19.5 minutes vs. 85.8 ± 18.7 minutes, $P = .001$). The extra steps of coracoid dissection, coracoid tracker placement, and glenoid registration with the stylus likely contributed to this increase in operative time. However, the time was likely inflated by the learning curve associated with the use of new instrumentation and a new technique. Prior studies using the same system and a similar technique documented 1.2- and 6-minute increases in operative time.[1,28] The decreased intraoperative time cited in these studies likely better represents our current practice, post-learning curve.

There are a number of limitations to our study. Because of the lack of preoperative CT scans, 14 patients in the non-navigated group were not able to be included in the analysis of glenoid morphology. There were differences between the 2 cohorts in terms of glenoid retroversion and the posterior subluxation index. Although the differences were statistically significant, they were unlikely to be clinically significant. The finding of an increased individual screw length with use of navigation must be interpreted with caution, as we were unable to assess the actual intraosseous length of the screws without subjecting patients to additional CT scans. We did not quantify screw length per screw position in our study, which may be of biomechanical relevance. This study does not provide biomechanical evidence of increased glenoid baseplate stability or accuracy of final implant position using augmented baseplates. However, our results do reflect the impact that navigation technology has had on the practice of the surgeons involved in this study. Long-term follow-up is the next logical step in our investigation. Further studies will examine clinical outcomes and early loosening rates associated with navigated rTSA.

Conclusion

Intraoperative computer navigation allowed for a longer individual screw length, an increased composite screw length, fewer total screws used, and an increased frequency of 2 screws used in total. Preoperative templating software led to a drastic increase in augmented glenoid baseplate use. The role of navigation and preoperative templating in rTSA is still evolving, but their use in this study significantly impacted surgical planning and the intraoperative technique.

Disclaimer

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References

1. Barrett I, Ramakrishnan A, Cheung E. Safety and efficacy of intraoperative computer-navigated versus non-navigated shoulder arthroplasty at a tertiary referral. Orthop Clin North Am 2019;50:95–101. https://doi.org/10.1016/j.ocl.2018.08.004.
2. Bercik MJ, Kruse K II, Yalizis M, Gauci MO, Chaoui J, Walch G. A modification to the Walch classification of the glenoid in primary glenohumeral osteoarthritis using three-dimensional imaging. J Shoulder Elbow Surg 2016;25:1601–6. https://doi.org/10.1016/j.jse.2016.03.010.
3. 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.
4. Bitzer A, Rojas J, Patten IS, Joseph J, McFarland EG. Incidence and risk factors for aseptic baseplate loosening of reverse total shoulder arthroplasty. J Shoulder Elbow Surg 2018;27:2145–52. https://doi.org/10.1016/j.jse.2018.05.034.
5. Chebli C, Huber P, Watling J, Bertelsen A, Bicknell RT, Matsen F III. 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.
6. Exactech. Extremities operative technique: Equinoxe platform shoulder system. 2017. https://www.exac.com/extremities/equinoxe-reverse-system/. Accessed August 19, 2019.
7. Frankle M, Siegal S, Pupello D, Saleem A, Mighell M, Vasey M. The reverse shoulder prosthesis for glenohumeral arthritis associated with severe rotator cuff deficiency. A minimum two-year follow-up study of sixty patients. J Bone Joint Surg Am 2005;87:1697–705. https://doi.org/10.2106/JBJS.D.02813.
8. Friedman RJ, Hawthorne KB, Genez BM. The use of computerized tomography in the measurement of glenoid version. J Bone Joint Surg Am 1992;74:1032–7.
9. Hart ND, Clark JC, Wade Krause FR, Kissenberth MJ, Bragg WE, Hawkins RJ. Glenoid screw position in the Encore Reverse Shoulder Prosthesis: an anatomic dissection study of screw relationship to surrounding structures. J Shoulder Elbow Surg 2013;22:814–20. https://doi.org/10.1016/j.jse.2012.08.013.
10. Hoenig MP, Loeffler B, Brown S, Peindl R, Fleischli J, Connor P, et al. Reverse glenoid component fixation: is a posterior screw necessary? J Shoulder Elbow Surg 2010;19:544–9. https://doi.org/10.1016/j.jse.2009.10.006.
11. Humphrey CS, Kelly JD II, Norris TR. Optimizing glenosphere position and fixation in reverse shoulder arthroplasty, part two: the three-column concept. J Shoulder Elbow Surg 2008;17:595–601. https://doi.org/10.1016/j.jse.2008.05.038.
12. 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. https://doi.org/10.2106/JBJS.N.00493.
13. Irlenbusch U, Kohut G. Evaluation of a new baseplate in reverse total shoulder arthroplasty—comparison of biomechanical testing of stability with roentgenological follow up criteria. Orthop Traumatol Surg Res 2015;101:185–90. https://doi.org/10.1016/j.otsr.2014.11.015.
14. James J, Huffman KR, Werner FW, Sutton LG, Nanavati VN. Does glenoid baseplate geometry affect its fixation in reverse shoulder arthroplasty? J Shoulder Elbow Surg 2012;21:917–24. https://doi.org/10.1016/j.jse.2011.04.017.
15. Kennon JC, Lu C, McGee-Lawrence ME, Crosby LA. Scapula fracture incidence in reverse total shoulder arthroplasty using screws above or below metaglene central cage: clinical and biomechanical outcomes. J Shoulder Elbow Surg 2017;26:1023–30. https://doi.org/10.1016/j.jse.2016.10.018.
16. Königshausen M, Jettkant B, Sverdlova N, Ehlert C, Gessmann J, Schildhauer TA, et al. Influence of different peg length in glenoid bone loss: a biomechanical analysis regarding primary stability of the glenoid baseplate in reverse shoulder arthroplasty. Technol Health Care 2015;23:855–69. https://doi.org/10.3233/THC-151031.
17. Lung TS, Cruickshank D, Grant HJ, Rainbow MJ, Bryant TJ, Bicknell RT. Factors contributing to glenoid baseplate micromotion in reverse shoulder arthroplasty: a biomechanical study. J Shoulder Elbow Surg 2019;28:648–53. https://doi.org/10.1016/j.jse.2018.09.012.
18. Matsumura N, Ogawa K, Kobayashi S, Oki S, Watanabe A, Ikegami H, et al. Morphologic features of humeral head and glenoid version in the normal glenohumeral joint. J Shoulder Elbow Surg 2014;23:1724–30. https://doi.org/10.1016/j.jse.2014.02.020.
19. Nashikkar PS, Scholes CJ, Haber MD. Role of intraoperative navigation in the fixation of the glenoid component in reverse total shoulder arthroplasty: a clinical case-control study. J Shoulder Elbow Surg 2019;28:1685–91. https://doi.org/10.1016/j.jse.2019.03.013.
20. Nguyen D, Ferreira LM, Brownhill JR, King GJ, Drosdowech DS, Faber KJ, et al. Improved accuracy of computer assisted glenoid implantation in total shoulder arthroplasty: an in-vitro randomized controlled trial. J Shoulder Elbow Surg 2009;18:907–14. https://doi.org/10.1016/j.jse.2009.02.022.
21. Parsons M, Greene A, Polakovic S, Byram I, Cheung E, Jones R, et al. Assessment of surgeon variability in preoperative planning of reverse total shoulder arthroplasty: a quantitative comparison of 49 cases planned by 9 surgeons. J Shoulder Elbow Surg 2020;29:2080–8. https://doi.org/10.1016/j.jse.2020.02.023.
22. Roche C, DiGeorgio C, Yegres J, VanDeven J, Stroud N, Flurin PH, et al. Impact of screw length and screw quantity on reverse total shoulder arthroplasty glenoid fixation for 2 different sizes of glenoid baseplates. JSES Open Access 2019;3:296–303. https://doi.org/10.1016/j.jses.2019.08.006.
23. Rouleau DM, Kidder JF, Pons-Villanueva J, Dynamidis S, Defranco M, Walch G. Glenoid version: how to measure it? Validity of different methods in two-dimensional computed tomography scans. J Shoulder Elbow Surg 2010;19:1230–7. https://doi.org/10.1016/j.jse.2010.01.027.
24. Routman HD, Flurin PH, Wright TW, Zuckerman JD, Hamilton MA, Roche CP. Reverse shoulder arthroplasty prosthesis design classification system. Bull Hosp Jt Dis (2013) 2015;73(Suppl 1):S5–14.
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. Verborgt O, De Smedt T, Vanhees M, Clockaerts S, Parizel PM, Van Glabbeek F. Accuracy of placement of the glenoid component in reversed shoulder arthroplasty with and without navigation. J Shoulder Elbow Surg 2011;20: 21−6. https://doi.org/10.1016/j.jse.2010.07.014.
27. Walch G, Badet R, Boulahia A, Khoury A. Morphologic study of the glenoid in primary glenohumeral osteoarthritis. J Arthroplasty 1999;14:756−60.
28. Wang AW, Hayes A, Gibbons R, Mackie KE. Computer navigation of the glenoid component in reverse total shoulder arthroplasty: a clinical trial to evaluate the learning curve. J Shoulder Elbow Surg 2020;29:617−23. https://doi.org/10.1016/j.jse.2019.08.012.
29. Werner BS, Hudek R, Burkhart KJ, Gohlke F. The influence of three-dimensional planning on decision-making in total shoulder arthroplasty. J Shoulder Elbow Surg 2017;26:1477−83. https://doi.org/10.1016/j.jse.2017.01.006.
30. Zumstein MA, Pinedo M, Old J, Boileau P. Problems, complications, reoperations, and revisions in reverse total shoulder arthroplasty: a systematic review. J Shoulder Elbow Surg 2011;20:146−57. https://doi.org/10.1016/j.jse.2010.08.001.