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The glenoid-intramedullary humeral angle: a measurement of compensatory scapular abduction in advanced rotator cuff arthropathy and its potential effects on implant choice

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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 Case-Control Design; Prognosis Study

Background: This study establishes measurements to evaluate pathologic compensation in rotator cuff tear arthropathy and resultant considerations for reverse shoulder arthroplasty.

Methods: Radiographs of patients with intact rotator cuffs were measured establishing interobserver and intraobserver reliability. Reverse shoulder arthroplasty cases performed by a single surgeon were then retrospectively reviewed. One year of follow-up radiographs were required for inclusion. Preoperative radiographs were analyzed for relative humeral head elevation ratio and humeral abduction relative to the glenoid face, termed the glenoid-intramedullary humeral angle. Statistical analyses assessed associations for radiographic measurements with presence and severity of scapular notching based on the Nerot-Sirveaux classification system.

Results: A total of 221 patients met inclusion criteria. At the 1-year follow-up, 61 (27.6%) shoulders had radiographic notching. There was a moderately strong ($r = -0.56$) negative correlation between glenoid-intramedullary humeral angle and humeral head elevation ratio. Patients with humeral head elevation ratio $\geq$ 20% were significantly ($P = .024$) and 9.2 times more likely to have notching of any grade. Patients with glenoid-intramedullary humeral angle $\leq$ 5 degrees were significant ($P < .0001$) and 6.7 times more likely to have notching of any grade and significantly ($P = .00018$) and 145 times more likely to have high-grade (3 and 4) notching.

Conclusions: Preoperative humeral head elevation and compensatory scapular rotation with relative adduction of the humerus have significant associations with high-grade notching. These radiographic findings have potential to help surgeons in preoperative decision-making regarding implant choice and patient education.

Reverse total shoulder arthroplasty (RTSA) is a standard-of-care surgical option for older patients with rotator cuff deficiency–associated painful loss of motion, rotator cuff tear arthropathy, proximal humerus fractures requiring arthroplasty, and revision TSA.[29] Historically, early failure rates were associated with aseptic loosening of the glenoid component. However, decreasing constraint and optimized fixation options have contributed to a decreased rate of loosening.[16] A 2018 systematic review confirmed improved outcomes in association with both medialized and lateralized center of rotation prosthesis with either 155 degree or 135 degree resultant humeral neck-shaft angles.[10]

Even with these documented improvements, a persistent complication associated with reverse shoulder arthroplasty is notching, resulting in varying amounts of inferior glenoid bone loss.[17] Notching is caused by bony impingement of the humeral implant against the inferior and posterior edge of the glenoid during adduction with reported incidence being between 5% and 100% of cases.[6,9] This bone loss is concerning with respect to progression and eventual loss of fixation of the glenoid baseplate.[3,4,21,22]

Our research was allowed under Institutional Review Board 1210395 (there was a waiver/alteration to a similar study that was used for this project, referred to as Amendment 125446).

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Falaise et al[5] demonstrated a potential relationship for notching with identifiable preoperative factors, including body mass index and the glenometaphyseal angle. To further delineate modifiable risk factors for this common complication, the present study was designed to investigate measurable preoperative radiographic characteristics that may be associated with notching and therefore influence technique and/or implant choice for RTSA. The selected measurements were based on the authors' clinical experiences and impressions in patient selection and outcomes for RTSA and included the following: (1) extrinsic superior tilt of the final glenosphere construct relative to the humeral shaft as measured by the novel glenoid-intramedullary humeral angle (GIHA) (Fig. 1); (2) humeral center elevation (HHE) ratio (Fig. 2) as previously described by Keener et al[13] with respect to rotator cuff tears; and (3) an analysis inspired by the "Gothic Arch" concept described by Krishnan et al[15] for hemiarthroplasty.

Each of these measurements may signal superior migration of the humerus and/or compensatory rotation of the scapula resulting in extrinsic superior tilt of the final glenosphere in relation to the humeral shaft and associated notching. As such, characterizing these potential associations with postoperative notching may allow for perioperative modification of technique or implant choice to limit notching, mitigating this important complication of RTSA. Therefore, the present study was designed to test the hypothesis that HHE ratio and subsequent GIHA will have strong associations with presence and severity of scapular notching after RTSA.

Materials and methods

After obtaining approval from our institutional review board, we initially identified 25 patients undergoing primary anatomic total shoulder arthroplasty with verified intact rotator cuffs at the time of surgery. GIHA was measured on upright, true AP (Grashey) x-rays, taken with the same calibrated technique, at our institution. This was accomplished by drawing a line from the most superior point of the glenoid to the most inferior point of the glenoid (the glenoid face). The intramedullary humeral line was drawn between two mid-diaphyseal points in the humeral shaft. The resultant Cobb angle between the lines is the GIHA (Fig. 1).

To determine reliability, repeatability, and precision of the GIHA measurement, the radiographs were measured in a random order by two investigators who were blinded to patient demographics and all other measurements. After each investigator completed measurements for all 25 subjects, the same radiographic studies were rerandomized and each investigator measured each 1 again at a separate time point. Interobserver reliability was determined by calculating the correlation coefficient (r^2) between the two investigators' measurements for all 50 readings using Pearson product-moment correlation tests. Intraobserver repeatability was determined by calculating the correlation coefficient (r^2) for each investigator's measurements for each session using Pearson product-moment correlation tests. Precision was determined by comparing all 50 measurements between investigators to determine differences in measured angle to calculate the mean, range, and 95% confidence interval.

Next, a retrospective review of cases was completed for a single surgeon at a single institution over a 10-year period. Only patients undergoing RTSA for massive rotator cuff tear or rotator cuff tear arthropathy were included. Patients undergoing reverse shoulder arthroplasty for osteoarthritis with biconcave (B2) glenoids, fracture, or revision were excluded, as these were felt to be unique diagnoses not generally resulting in superior elevation/migration of the humerus. Inclusion criteria were defined as patients with preoperative shoulder radiographs performed at our institution, those undergoing reverse shoulder arthroplasty and those having at least 1-year radiographic follow-up or notching present on radiographs before 1 year. Adequate preoperative radiographs were defined as those allowing accurate measurement of glenoid height, humeral head size, and relative heights of each, using standardized digital markers for calibration. Upright (standing) true anterior to posterior views of the glenohumeral joint (Grashey view) were used. Adequate postoperative radiographs required a Grashey view to evaluate and measure notching as previously (described by Lévigne et al[17]). After complete review with the full application of inclusion and exclusion criteria, 221 patients were included in the study. Radiographs of the 221 patients meeting inclusion criteria were analyzed using embedded software for manipulation and measurement of the images as described in the following text.

HHE ratio

A line connecting the inferior and superior borders of the glenoid face was drawn. A perpendicular line to the inferior edge of the glenoid face was drawn across the humerus. A line parallel to the glenoid face was measured from the previous line to the inferior articular edge of the humeral head, establishing the relative elevation of the humeral head. HHE ratios were measured relative to the length of the glenoid face to obtain a percent of elevation, eliminating discrepancies in magnification and image source (Fig. 3).

Glenoid-intramedullary humeral angle

The Cobb angle is formed by reference lines along the glenoid face and the intramedullary axis of the humerus on a Grashey view of the shoulder. The line of the glenoid face was drawn between one point at the superior most point of the glenoid and another point at the inferior most point of the glenoid. Intramedullary axis of the humerus was determined by connecting two mid-diaphyseal points of the humerus. As measured previously, as the GIHA gets smaller, there is less abduction of the humeral shaft relative to the

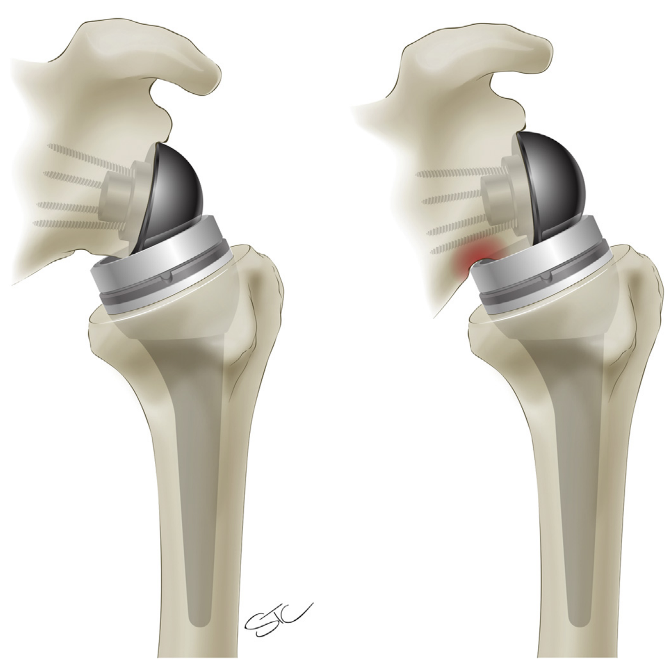

Figure 1 Illustration of implant contact during scapular rotation with unchanged glenoid implant position.

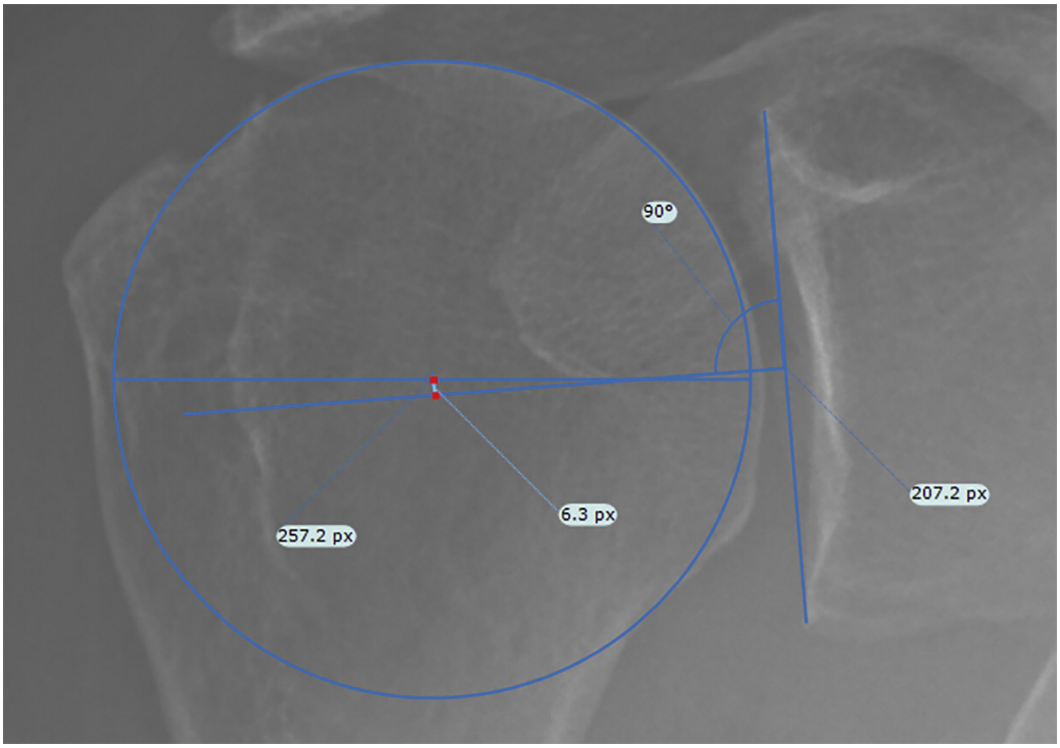

Figure 2 Radiographic analysis of humeral head center (best fit) elevation relative to center of glenoid. The amount (6.3) in this analysis is then normalized to the glenoid face (207.2) to give a percentage elevation (3%).

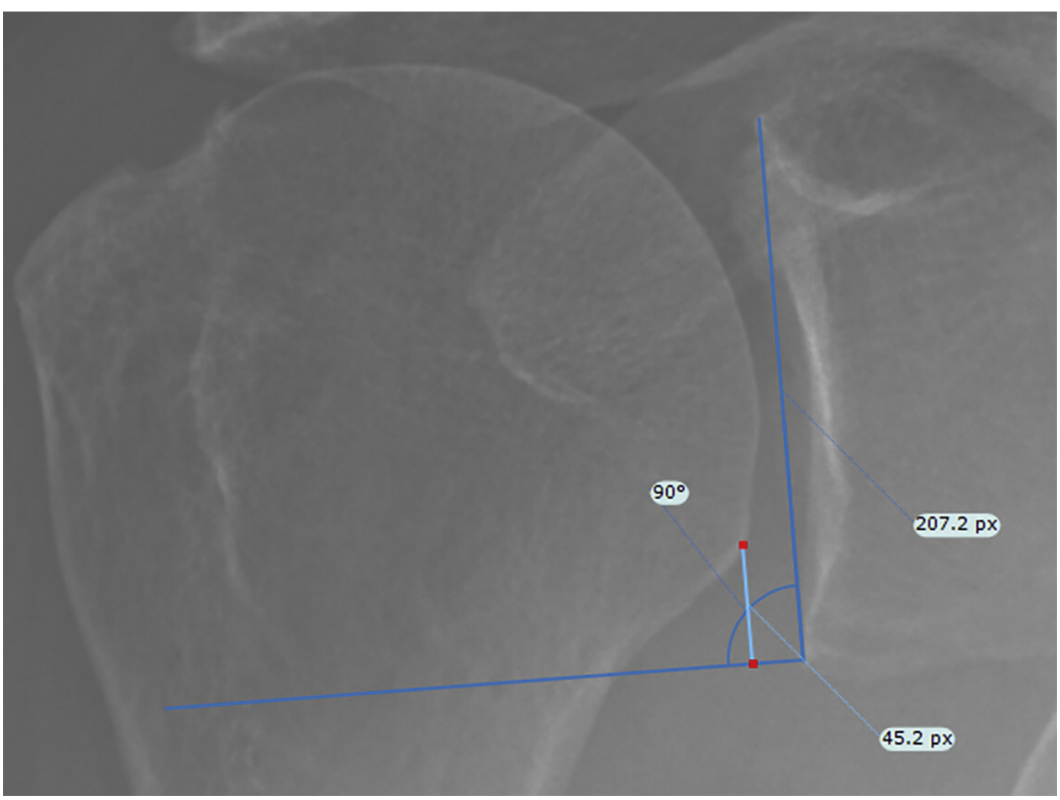

Figure 3 Elevation of the humeral head and breaking of the "Gothic arch." The amount of elevation (45.2) is divided by the height of the glenoid (207.2) to give a percentage elevation (21%).

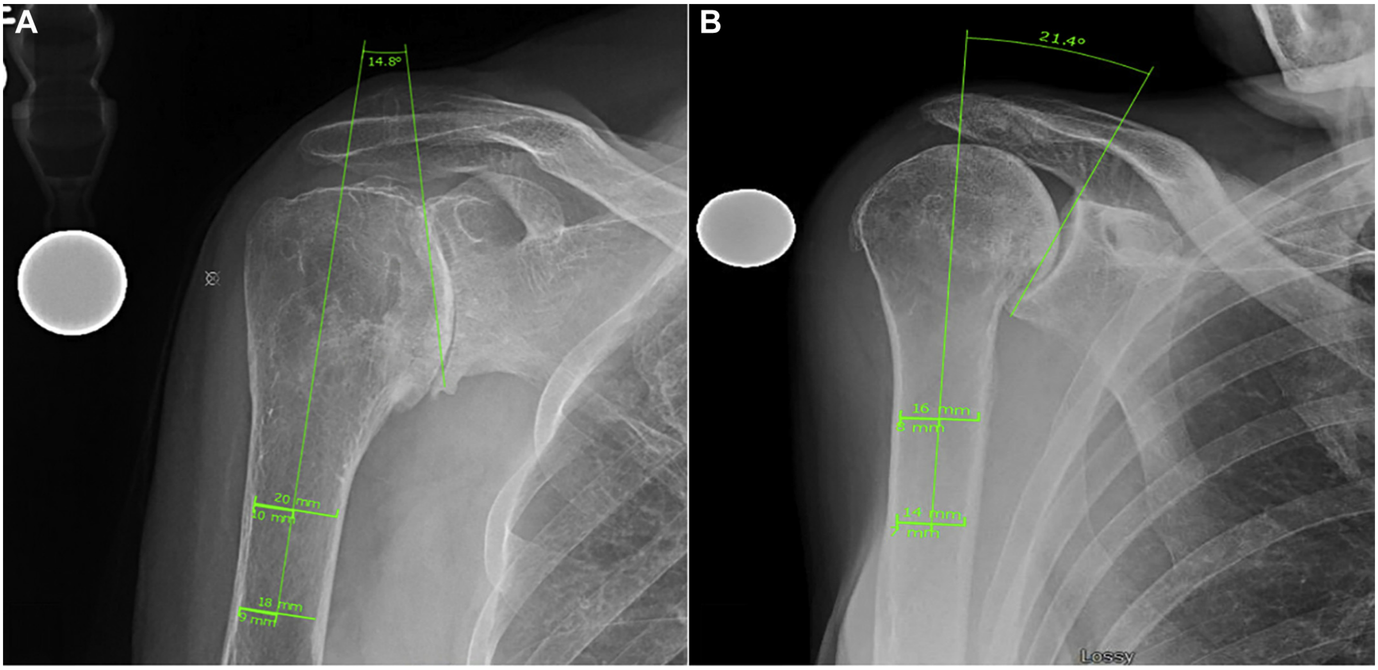

Figure 4 Two example measurements of the glenoid-intramedullary humeral angle (GIHA). (**A**) A positive (abducted) GIHA in a patient with standard glenohumeral arthritis. (**B**) A negative (adducted) GIHA in a patient with rotator cuff arthropathy.

glenoid face. As it becomes negative, there is increasing adduction of the humeral shaft relative to the glenoid face (Fig. 4).

Notching grade

An independent reviewer graded notching (Nerot grade 1-4) on follow-up radiographs, as previously described by Lévigne et al.[17] Patients with insufficient (< 1 year) radiographic follow-up were included in the study if they demonstrated notching on radiographic follow-up before 1 year. These patients also were deemed to have early notching.

Control cohort

To further investigate the effects of preoperative compensatory abduction of the scapula on subsequent notching, reverse shoulder arthroplasties (n = 41) performed to treat acute fractures using a 155-degree fracture-specific humeral stem with a medialized glenosphere by the same surgeon at the same institution during the same time period were reviewed for subsequent notching. Cases were included in this cohort when patient questionnaires and histories revealed no preinjury shoulder difficulties, pathologies, or treatment.

Statistical analysis

Descriptive statistics were calculated for all measures. Strength of correlations among measures was determined using Pearson's or Spearman's analyses. HHE ratios and GIHA were compared for significant differences based on notching grade using 1-way ANOVA and for severity of notching (G0-2 vs. G3,4) using a t-test. Clinically relevant thresholds were assigned based on mean values for HHE ration and GIHA, and then, chi-square or Fisher's exact tests were used to determine differences in proportions with respect to presence and severity of notching. Odds ratios were calculated when significant differences in proportions were noted. Significance was set at $P < .05$.

Results

Intraobserver correlation coefficents for GIHA were as follows: observer 1 $r^2 = 0.99$; observer 2 $r^2 = 0.98$. Interobserver correlation coefficent was Obs1-Obs2 $r^2 = 0.94$. Mean difference in measured angles between observers was 2.6 degrees (range, 0-11.2, 95% CI = 1.7-3.5).

At a minimum 1-year follow-up, 61 (27.6%) patients had radiographic notching (Nerot grade ≥ 1). There was a moderately strong negative correlation between HHE ratio and GIHA (r = -0.56), moderately strong positive correlation between HHE ratio and notching grade (r = 0.4), and moderately strong negative correlation between GIHA and notching grade (r = -0.43). (Table I)

The HHE ratio was significantly lower ($P = .0002$) in patients with no notching than in patients with notching of any grade and significantly higher ($P = .029$) in patients with high-grade (G3,4) notching. Patients with HHE ratio ≥ 20% were significantly ($P = .024$) and 9.2 times more likely to have notching of any grade (Table II).

For the fracture-control cohort, the notching incidence was 2%.

Discussion

The results of this study allowed us to accept our hypothesis in that HHE ratio and GIHA had important associations with presence and severity of postoperative scapular notching. The goal of characterizing preoperative radiographic findings that could serve as risk factors for subsequent notching in the postoperative period mirrors similar efforts in the total knee and hip arthroplasty literature to account for anatomic abnormalities (lateral femoral condyle hypoplasia for total knees and dysplasia of the acetabulum) that may help surgeons mitigate complications.[3,8,20,24]

Table I
Correlation coefficients (r) for HHE ratio, GIHA, and notching grade.

	HHE ratio	GIHA
Nerot grade	0.4	−0.43
HHE ratio	-	−0.56

GIHA, glenoid-intramedullary humeral angle; *HHE*, humeral head elevation.

Table II
Odds ratios for notching based on preoperative measurement thresholds.

Threshold	Notching	G3-4 notching	Early notching
HHE ratio ≥ 20%	5.6x	NSD	9.2x
GIHA < 5	6.7x	145x	9.8x
-GIHA	15x	340x	22x

GIHA, glenoid-intramedullary humeral angle; *HHE*, humeral head elevation; *NSD*, no standard deviation.

Furthermore, the recently described reverse shoulder angle demonstrated the potential to underestimate correction and resultant superior inclination of the baseplate, especially in patients with increased central wear within the glenoid.[2] The utility in the GIHA is its measurement of the relationship of the humeral shaft to the glenoid face which, in theory, determines a patient's risk for notching.

These preoperative factors can influence the surgical technique and choice of implants to improve outcomes. Elevation of the humeral head greater than 20% relative to the glenoid is associated with compensatory scapular abduction leading to adduction of the humerus relative to the glenoid face and higher-grade notching in a postoperative follow-up in this study. The data suggest that persistent adduction of the humerus, or returning to the preoperative state, after surgery increases the likelihood and severity of notching. As the decompensated patients progressed from surgery, the scapula returns to the preoperative state bringing the humerus into relatively higher degrees of adduction, contacting the glenoid neck and lateral scapula. To provide further support for the effects of preoperative compensatory abduction of the scapula on subsequent notching, reverse shoulder arthroplasties performed to treat acute fractures using a 155-degree fracture-specific humeral stem were assessed for subsequent notching. For this fracture-control cohort, notching incidence was 2%, suggesting that preoperative compensatory abduction of the scapula increases the likelihood of notching when a 155-degree humeral stem is used for RTSA.

Scapular notching is a known complication of RTSA[6,9]; however, debate continues regarding the clinical implications of scapular notching after RTSA. Early studies suggested that scapular notching was a "normal phenomenon" that occurred without definitive implications for patient-reported outcomes or prosthesis failures.[27,29] More recently, however, multiple studies have provided clear evidence for scapular notching, especially higher-grade notching, being associated with detrimental clinical consequences.[18,23,24,28] For example, Mollon et al[18] assessed 476 RTSAs and reported significantly lower postsurgical American Shoulder and Elbow Surgeons, Constant, Simple Shoulder Test, and University of California-Los Angeles shoulder scores in patients with scapular notching than in those without scapular notching at a mean follow-up of 38 months. There are now studies showing notching can be progressive and can lead to early glenoid component loosening.[3,4,21,22]

Other preoperative risk factors that have shown prevalence for notching as well include body mass index < 30 and increased preoperative range of motion.[12] Radiographic signs of patients at risk for notching have previously been described by our group, specifically at scapular neck length < 9 mm.[19] Our study attempts to add additional preoperative radiographic findings that will help in predicting postoperative notching.

Biomechanical studies, patient anatomy, and postoperative implant placement analyses have identified multiple factors contributing to notching. Given this information, surgeons have adjusted their surgical technique to place the glenoid baseplate inferiorly and with inferior tilt.[1,9,19] There is evidence to suggest that surgical technique has some effects on the occurrence of scapular notching through lateralization of the glenoid component, as well as inferior placement and inferior tilt of the glenoid component.[2,7,11] Kempton et al[14] showed that despite these interventions, notching can still occur at a rate comparable with those previously reported. Lateralizing the center of rotation is associated with decreased notching, but there are limits to lateralization.[7,11] Despite the identification of contributing factors and the modification of surgical techniques and implants, the rate of notching has not significantly decreased.[4,26] Our study shows evidence that patients with a significantly negative GIHA will have persistent relative adduction of the humeral shaft in relation to the glenoid baseplate, despite being placed inferiorly and with inferior tilt. This is due to the scapular rotation. As the scapula rotates into abduction, the glenoid face tilts superiorly.

To further illustrate this concept, we used commercially available, manufacturer-specific software to plan a case with a GIHA of -14.8. The resting position of the scapula with the arm at the side illustrates the following scenarios:

A. Starting relationship of the joint and total correction needed to allow baseplate to be in a neutral position.
B. Relationship of the humeral component to the scapula with traditional correction (10 degrees inferior tilt and medialization for baseplate support).
C. Baseplate wedge support correcting tilt and lateralizing the construct.
D. Straight lateralization with baseplate perpendicular to the glenoid face (Fig. 5).

Both medialized and lateralized centers of rotation in RTSA have been shown to have good clinical results.[3,25] Our study simply attempts to further establish the presence of radiographic signs that can help identify patients that may be at risk of scapular notching preoperatively, thus allowing the surgeon the opportunity to modify their technique in hopes of decreasing the chance that high-grade scapular notching might occur.

Limitations of this study include the retrospective design limiting the capabilities for providing patient outcomes data, and therefore, this initial study was focused on the objective of characterizing potential clinically useful methods for determining preoperative risk for subsequent notching. Future studies should include a greater number of patients evaluated prospectively using diagnostic and treatment-based cohorts.

Conclusions

Ultimately, this study presents a clinically applicable and reproducible measurement to evaluate patient factors associated with notching. The data suggest that patients with > 20% migration and/or negative GIHA may benefit from lateralization of the glenoid component. Considering these findings, the authors recommend evaluating HHE ratio and GIHA on preoperative radiographs and recommend against a traditional 155-degree medialized, construct in patients with severe superior migration, and/or compensatory abduction of the scapula. Further study is warranted to evaluate

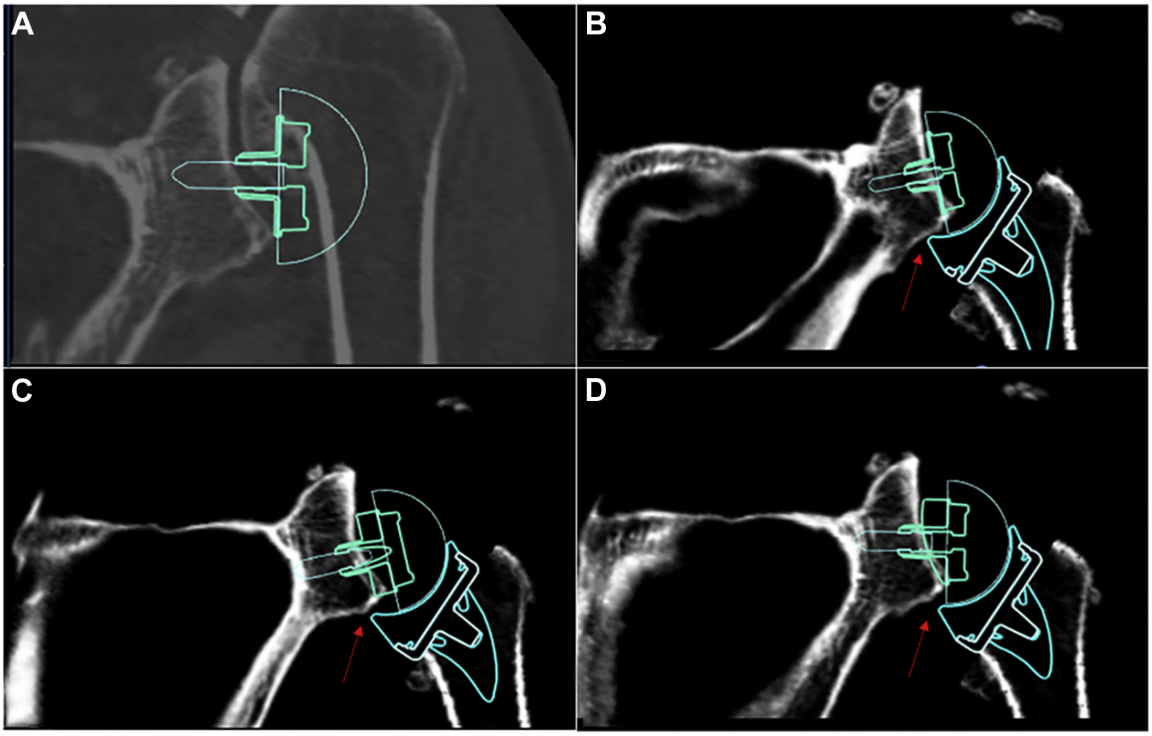

Figure 5 (**A**) Total correction needed to allow for neutral baseplate. (**B**) Relationship of the humeral component to the glenoid with traditional correction of inferior translation and inferior tilt of 10 degrees. (**C**) Relationship of the humeral component to the glenoid with use of a lateralized baseplate (**D**) use of a lateralized component with wedge support to simultaneously correct tilt. The ↗ points to an increasing distance between the inferior glenoid neck and the humeral components as different components are used from Figure B to D.

these results and the most appropriate way to modify surgical technique to decrease rate of notching after RTSA.

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