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Multiplanar analysis of proximal humerus anatomy of patients with rotator cuff arthropathy and relevance to reverse shoulder press-fit stems

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Background: Short stems have become increasingly popular in reverse shoulder arthroplasty (RSA) due to their ability to preserve bone stock for revision surgery. However, short stems may be more at risk for malalignment or loosening, and commercially available stems have varied designs. The purpose of this study was to perform a multiplanar analysis of proximal humerus anatomy in patients with rotator cuff arthropathy to better define canal geometry and identify differences based on sex.

Methods: A retrospective review was performed of a consecutive series of patients undergoing RSA for rotator cuff arthropathy. A total of 117 patients were identified with preoperative computed tomography scans. Measurements were undertaken following multiplanar reconstruction of the computed tomography scans. Measured parameters included the following: transition point (TP), anteroposterior (AP) and mediolateral (ML) distances, intramedullary (IM) and bone diameter, and cortical thickness. The TP was defined as the distance from the periosteal border of the greater tuberosity to the level of the IM canal where the endosteal borders became parallel. Measurements started at the metaphysis, and then proceeded 25 and 50 mm distal to the metaphysis followed by 10 mm increments thereafter. Each level was compared to the level above with *t* tests in the overall cohort and separately by sex. Height was correlated to ML-AP difference and IM diameter with Pearson correlation coefficient. Potential stem sizes that extended 50, 60, 70, and 80 mm from the metaphysis were analyzed to record the percentage of patients in whom the stem would reach past the TP.

Results: The mean TP for all patients was 55.6 ± 7.4 mm (37.5-78.4) from the greater tuberosity, 53.3 ± 6.6 mm (37.5-67.0) in females and 58.1 ± 7.5 mm (41.9-78.4) in males. ML and AP distances and IM diameter became consistent at level 3 (mean, 83 mm distal to the greater tuberosity) in the overall cohort and in both sexes. Height positively correlated with IM diameter. Males had significantly larger IM diameters compared to females at all levels. Cortical thickness remained relatively consistent throughout the proximal humerus. A stem length of 70 mm would extend past the TP in 98% of patients.

Conclusion: Humeral implants in RSA with a stem of at least 70 mm in length would extend distally past the TP in the majority of cases regardless of sex. At this point, the canal's area remains consistent which would facilitate diaphyseal fixation if required.

The initial Grammont reverse total shoulder arthroplasty (RTSA) utilized a long cylindrical stem that was cemented into the humeral canal.[16] As usage of RTSA has increased,[7] humeral components have evolved toward press-fit and shorter stems.[26] The goal of the latter is to achieve bone preservation, limit proximal stress shielding, and facilitate revision procedures if required.[10,25]

This is especially of interest as the complication rate after revision reverse shoulder arthroplasty has been reported as high as 40% and revision data support the concept that the operative time for the removal of short stems is reduced compared to standard length stems.[5,22] However, shorter stem length has potential tradeoffs

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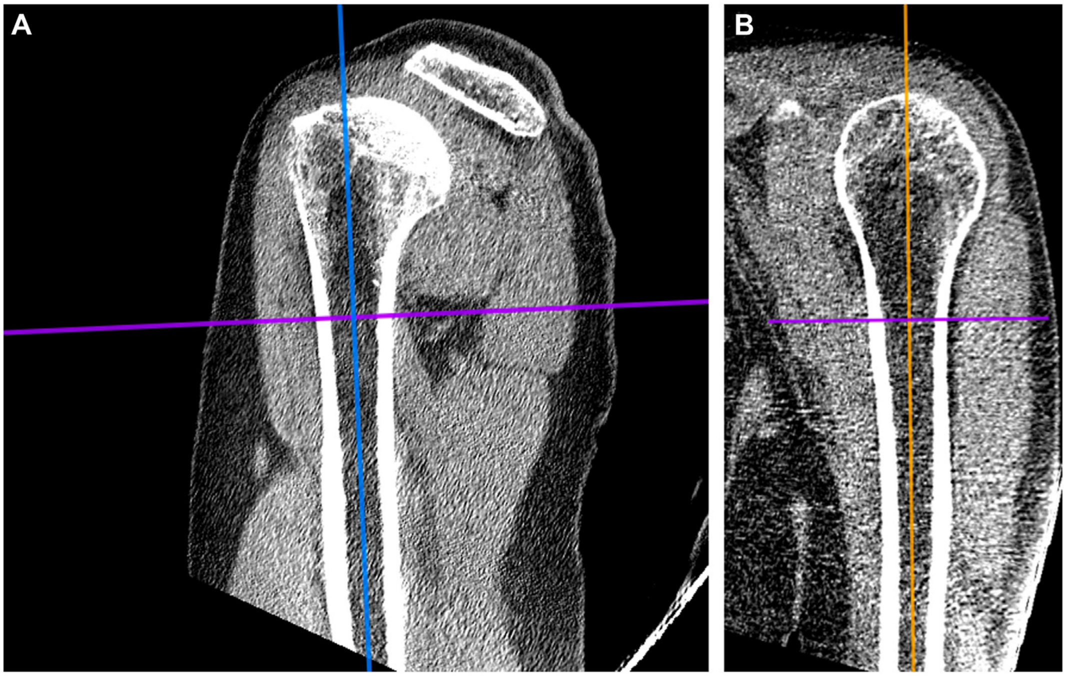

Figure 1 Left shoulder multiplanar views of the proximal humerus. (A) Coronal plane with the proximal to distal line (blue) bisecting the humeral canal and the transition point (purple line) shown where the endosteal borders become parallel. (B) Sagittal plane showing proximal to distal line bisecting the humeral canal.

including potential for malalignment and loosening. Current commercially available RTSA humeral stems come in a variety of lengths and geometries but are based on convention rather than anatomic evidence. Thus, further anatomic information may help identify the ideal stem length in order to optimize the current risk to benefit ratio of length for press-fit stem utilization.

The semiconstrained nature of the RTSA implant allows for bypassing the rotator cuff in patients with rotator cuff arthropathy (RCA).[20] RCA occurs from the loss of the rotator cuff's dynamic stabilizer function leading to irreversible bony changes, including acetabularization of the acromion and femoralization of the humeral head. These bony changes, especially humeral head wear, could have implications in implant length different than those used in patients with primary glenohumeral arthritis.[6]

The purpose of this study, therefore, was to perform a multiplanar analysis of proximal humerus anatomy in patients with a diagnosis of RCA to better define canal geometry and identify any differences based on sex. The authors hypothesized that humeral canal measurements would become consistent after a transition point (TP) in the humeral canal and that this point would be statistically more distal in men compared to women.

Methods

Study design

A retrospective review was performed on a consecutive series of patients who underwent RTSA at 3 institutions between March 2022 and September 2022. Upon institutional review board approval, CPT (Current Procedural Terminology) codes were used to screen for patients at each institution's data registry. No informed consent was required for this study, as all data were retrospective and deidentified. The inclusion criteria were a diagnosis of RCA and a preoperative computed tomography (CT) scan performed for preoperative planning with slice thickness less than 1 mm that extended to include at least 120 mm of the proximal humerus. The exclusion criteria were other shoulder pathologies (eg, humeral shaft or proximal humerus fractures, primary osteoarthritis, or tumor), revision surgery, or CT scans with insufficient slice thickness or scan coverage. A total of 117 patients fulfilled the study criteria, of which 57 patients were male and 60 female. For the overall cohort, the mean age at surgery was 72.3 years, which was comparable for both sexes. The mean age for females was 72.2 years and for males was 72.4 years. The mean height for the entire sample was 169.0 cm, with a mean height of 162.6 cm for females and 174.7 cm for males.

CT scan measurements

Prior to study commencement, a systematic measurement sequence was agreed upon between 2 authors (P.J.D. and J.A.). Measurements were completed by one author (J.A.) with Horos (LGPL-version 3.0), an open-source medical image viewer, which allows for multiplanar viewing of 2-dimensional CT. Initially, all planes were organized with the 3D MPR (multiplanar reformation) module. This allowed for a multiplanar display in the coronal, sagittal, and axial planes oriented anteroposteriorly (AP). While viewing the coronal and sagittal planes, a vertical line was oriented at the center of the intramedullary (IM) canal to bisect the distance from both endosteal borders (Fig. 1 *A* and *B*). As a result, the program automatically set the crossing point of the AP and mediolateral (ML) lines to the center of the IM canal in the axial plane.

All measurements were recorded in mm. First, using the coronal plane, the TP was measured for each patient. The "transition point" was defined as the distance from the periosteal border of the greater tuberosity (GT) to the level of the IM canal where the endosteal borders became parallel.[6]

Next, the distance between the humeral metaphysis and the most superior point of the GT was measured (Fig. 2 *A* and *B*). The level of metaphysis was identified as the most inferior margin of the humeral head without including osteophytes. At this level, the

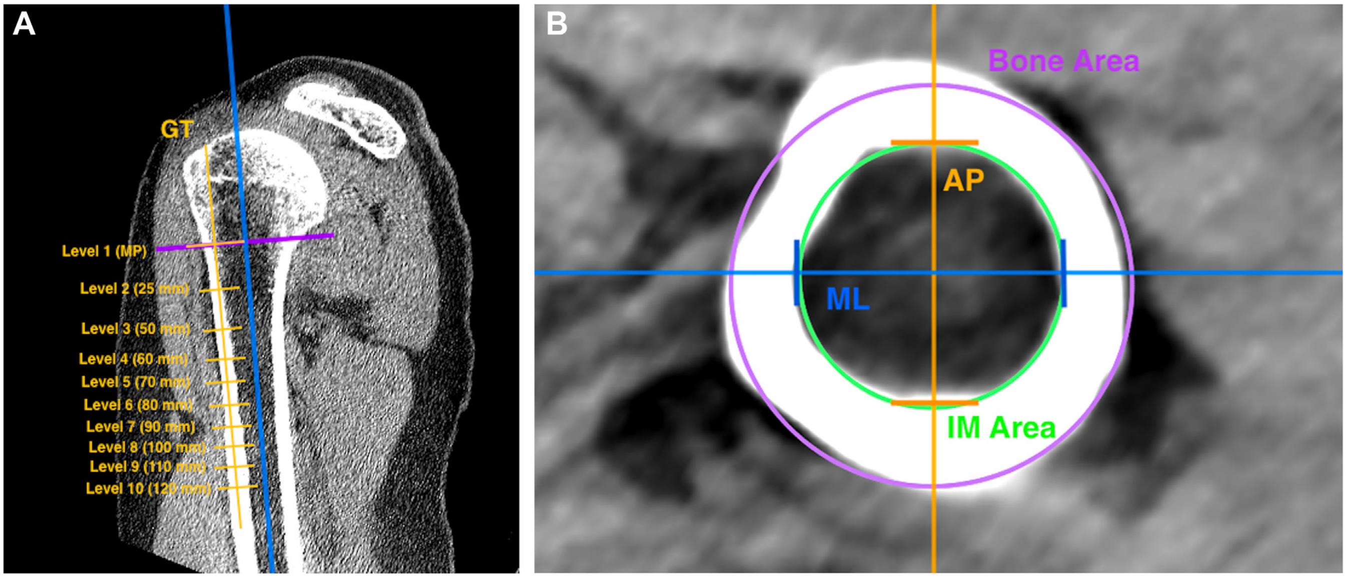

Figure 2 CT scan-multiplanar views demonstrating the measurement method used. (A) Coronal plane of the proximal humerus showing the measured levels starting from the GT to level 10 (120 mm distal to GT). Measurements began at the MP until reaching level 10. (B) Axial plane depicting the measurements undertaken at each level including AP (orange line) and ML (blue line) dimensions, and IM (green circle) and bone (purple circle) areas. *CT*; computed tomography; *GT*, greater tuberosity; *MP*, metaphysis; *AP*, anteroposterior; *ML*, mediolateral.

vertical and horizontal axes were set at the center on the coronal plane and measured the ML and AP distances of the IM canal on the axial plane. While viewing the latter, the area of the outer humeral cortex and inner IM canal were measured. The IM canal area was estimated with a perfect circle positioned inside the canal extending to the endosteal border while avoiding bone overlap. The bone area was sized with a circle around the periosteal border taking care to minimize empty space. The difference in diameters between these 2 areas was used to calculate cortical thickness. Following this, measurements were repeated at 25 and 50 mm distal to the MP, and then at every 10 mm thereafter. All collected data were entered and organized in Microsoft Excel (Version 16.65).

Statistical analysis

The mean measurements at each level and between sexes were compared with *t* tests. The following measurements were included in the analysis: MP, AP, IM and bone diameters, and cortical thickness. *P* values from each level to the level above were compared to determine the segment where the diameter became consistent, and the canal became cylindrical using the IM diameter and ML and AP difference, respectively. Pearson correlation coefficients were utilized to evaluate for a linear bivariate relationship between height and humeral canal measurements.[27] In addition, the percentage of patients in whom a hypothetical stem length of 50, 60, 70, or 80 mm reached past their TP was calculated. This analysis was performed for the complete set of patients and separately by sex. *P* values under .05 were considered statistically significant. *T* tests and Pearson correlation coefficients were calculated with SPSS (Version 28, IBM, Armonk, NY, USA).

Results

GT to metaphysis and transition point

Overall, the mean TP from the tip of the GT was 55.6 ± 7.4 mm and the mean distance from the GT to MP was 33.4 ± 4.1 mm. In females, the mean TP from the GT was 53.3 ± 6.6 mm and the GT to MP distance was 32.3 ± 4.0 mm. Males had larger mean distances, with the TP from the GT and GT to MP distance at 58.1 ± 7.5 mm ($P = .002$) and 34.7 ± 3.9 mm ($P < .001$), respectively.

IM canal measurements

Canal measurements per level for the entire cohort are provided in Table I. When comparing both AP and ML distances between levels, there were no statistically significant differences in the parameters beyond level 3 ($P = .043$ vs. level 4) which corresponds to a length of 83 mm distal to the GT. This meant the IM canal became consistently cylindrical after measurement level 4. When comparing AP and ML difference, the IM canal's shape remained uniform throughout the proximal humerus. The IM diameter also became consistent at level 3 ($P = .103$ vs. level 4). Cortical thickness was statistically similar from levels 3 to 7 ($P > .05$), and from levels 9 to 10 ($P > .05$). Thickness increased significantly at level 8 and remained consistent thereafter.

Female vs. male sex comparison

Female and male sex data are displayed in Tables II and III, respectively. For females, there was no difference in IM diameter and both parameters (ML and AP) after level 3 which corresponded to 82 mm distal to the GT ($P > .05$). The AP-ML difference remained consistent beyond level 2 ($P > .05$). Cortical thickness remained statistically similar throughout the proximal humerus ($P > .05$). For males, there was no statistical difference in AP, ML, and IM diameter after level 3 corresponding to 85 mm distal to the GT. AP-ML difference became relatively consistent after level 2 ($P > .05$). There was no statistically significant difference in cortical thickness after level 2 ($P > .05$).

When comparing both sexes, IM diameter was statistically smaller in females at all levels ($P < .001$) (Table IV). In contrast, ML-AP difference was similar at all levels ($P > .05$) suggesting that both sexes have a similar IM canal shape throughout the proximal humerus. Cortical thickness analysis showed significant differences at all levels ($P < .05$), except at levels 1 ($P = .282$) and 10 ($P = .149$).

Table I
Measurement summary for the entire cohort.

Level	Total distance (mm)	ML (mm)	*P* value vs. level above	AP (mm)	*P* value vs. level above	IM diameter (mm)	*P* value vs. level above	ML-AP difference (mm)	*P* value vs. level above	Cortical wall thickness	*P* value vs. level above
Level 1	33	29.9		28.9		26.0		4.4		7.4	
Level 2	58	18.3	<.001	18.0	<.001	16.9	<.001	1.7	<.001	7.9	.032
Level 3	83	15.4	<.001	15.7	<.001	14.5	<.001	1.4	.096	8.5	.039
Level 4	93	14.6	.043	15.0	.081	13.9	.103	1.3	.468	8.8	.320
Level 5	103	13.9	.071	14.5	.196	13.3	.097	1.3	1.000	9.3	.098
Level 6	113	13.2	.700	14.1	.292	12.9	.259	1.5	.147	9.8	.120
Level 7	123	12.7	.181	13.8	.422	12.5	.223	1.6	.507	10.3	.120
Level 8	133	12.3	.276	13.6	.585	12.2	.370	1.8	.167	11.0	.033
Level 9	143	11.8	.189	13.3	.446	12.0	.572	1.9	.489	11.3	.369
Level 10	153	11.2	.154	12.6	.117	11.5	.599	1.9	1.000	11.4	.765

ML, mediolateral; *AP*, anteroposterior; *IM*, intramedullar.

Table II
Summarized humerus measures for females.

Level	Total distance (mm)	ML (mm)	*P* value vs. level above	AP (mm)	*P* value vs level above	IM diameter (mm)	*P* value vs. level above	ML-AP difference (mm)	*P* value vs. level above	Cortical wall thickness (mm)	*P* value vs. level above
Level 1	32	28.0		26.4		23.4		4.5		7.2	
Level 2	57	16.5	<.001	16.1	<.001	15.0	<.001	1.5	<.001	7.4	.419
Level 3	82	13.9	<.001	14.2	<.001	13.0	<.001	1.3	.321	7.8	.197
Level 4	92	13.2	.084	13.7	.276	12.4	.070	1.3	1.000	8.1	.425
Level 5	102	12.6	.138	13.3	.373	11.9	.176	1.3	1.000	8.6	.227
Level 6	112	12.0	.147	13.2	.830	11.7	.587	1.6	.140	8.8	.635
Level 7	122	11.6	.353	12.9	.537	11.3	.226	1.8	.403	9.3	.247
Level 8	132	10.9	.113	12.6	.544	10.9	.226	1.8	1.000	10.0	.128
Level 9	142	10.3	.201	12.2	.453	10.4	.164	2.1	.192	10.6	.191
Level 10	152	9.5	.114	11.3	.139	10.2	.636	2.1	1.000	11.0	.373

ML, mediolateral; *AP*, anteroposterior; *IM*, intramedullar.

Height correlation

Overall, IM diameter was positively correlated with height (Table V). IM diameter was moderately correlated with height in levels 1 ($\rho = +0.0566$; $P < .001$) and 2 ($\rho = +0.597$, $P < .001$), and weakly correlated from levels 3 ($\rho = +0.474$; $P < .001$) to 9 ($\rho = +0.292$; $P = .003$) (Table IV). Although the correlation was weakly positive at level 10, the coefficient was insignificant ($\rho = +0.286$; $P = .082$). There was no statistically significant correlation between ML-AP diameter difference and height at each level ($P > .05$).

Stem length analysis

In the entire cohort, a potential stem length of 50 mm would extend past the TP in 24% of patients, including 33% of females and 14% of males. A potential stem length of 60 mm would reach the TP in 69% of patients which corresponds to 82% of women and 56% of men. A potential stem length of 70 mm would extend past the TP in 98% of patients, including 100% of females and 96% of males. A potential stem length of 80 mm would have reached past the TP in all patients.

Discussion

The primary findings of this study were based on the mean TP and IM measurements, and an RTSA stem length of 70 mm that would extend past the TP in 98% of patients and achieve diaphyseal fixation and stability. Furthermore, the transition to a cylindrical canal occurs at a shorter distance in females compared to males. These anatomic findings may have important implications for stem length design in RTSA for patients with RCA.

Traditionally, standard-length stems were implanted with cement. This provided additional stability to the construct with drawbacks of increased operative time and increasing difficulty of revision surgery, these challenges in part led to the advent of press-fit stems.[4,15,18] Most RTSA press-fit stems are purposefully designed to achieve meta-diaphyseal fixation.[11] Longer diaphyseal stems increase fixation and stability of the implant while compromising increased bone stock in the setting of revision surgery and potentially leading to higher rates of stress shielding as well as increased osteolysis in the primary setting.[13,24] Conversely, short-stem implants not achieving adequate metaphyseal fixation can predispose to component loosening and malalignment as demonstrated in TSA.[3,8] In some cases, a short-stem implant combining both diaphyseal and metaphyseal fixation could avoid this issue. The present study presents data demonstrating that a stem length of 70 mm would extend past the TP in 98% of patients and achieve diaphyseal fixation and stability. While in an RTSA design, the stem is under compression, an application of the information provided by the present study may optimize the current risk benefit ratio of length for press-fit stem utilization based on anatomic parameters.

Malalignment remains a concern with the use of short-stem RSA implants; however, the literature shows conflicting data on this point. While short stems have provided stability with metaphyseal fixation alone in some cases,[2] this study provides an anatomical basis to achieve further stability with press-fit designs. High rates of axial malalignment, up to 27.4%, have been reported in some studies,[1,9] whereas others have shown short stems to be placed in neutral alignment up to 95.6% of the time, and no difference in

Table III
Summarized humerus measures for males.

Level	Total distance (mm)	ML (mm)	P value vs. level above	AP (mm)	P value vs. level above	IM diameter (mm)	P value vs. level above	ML-AP difference (mm)	P value vs. level above	Cortical wall thickness (mm)	P value vs. level above
Level 1	35	31.8		31.6		28.7		4.4		7.5	
Level 2	60	20.1	<.001	19.9	<.001	18.9	<.001	1.8	<.001	8.4	.024
Level 3	85	16.9	<.001	17.2	<.001	16.1	<.001	1.4	.180	9.2	.097
Level 4	95	16.1	.157	16.4	.151	15.5	.249	1.3	.613	9.5	.499
Level 5	105	15.2	.101	15.6	.137	14.7	.097	1.3	1.000	10.0	.206
Level 6	115	14.3	.095	14.9	.201	14.0	.161	1.4	.595	10.6	.158
Level 7	125	13.7	.255	14.5	.456	13.6	.414	1.4	1.000	11.1	.239
Level 8	135	13.3	.431	14.3	.693	13.1	.317	1.7	.095	11.6	.239
Level 9	145	12.6	.177	14.0	.576	12.9	.694	1.7	1.000	11.7	.824
Level 10	155	12.4	.728	13.4	.328	12.8	.855	1.8	.643	11.7	1.000

ML, mediolateral; *AP*, anteroposterior; *IM*, intramedullar.

Table IV
Comparison of intramedullar diameter, mediolateral-anteroposterior difference, and cortical wall thickness between sexes at each level.

Comparison of key humeral measures between male and female sex												
	IM diameter				ML-AP difference				Cortical wall thickness			
	Male	Female	*Mean Diff.*	P value	Male	Female	*Mean Diff.*	P value	Male	Female	*Mean Diff.*	P value
Level 1	28.7	23.4	−5.4	<.001	4.4	4.5	0.1	.854	7.5	7.2	−0.3	.282
Level 2	18.9	15.0	−3.9	<.001	1.8	1.5	−0.3	.314	8.4	7.4	−1.1	.007
Level 3	16.1	13.0	−3.1	<.001	1.4	1.3	−0.1	.609	9.2	7.8	−1.4	.001
Level 4	15.5	12.4	−3.1	<.001	1.3	1.3	0.0	1.000	9.5	8.1	−1.3	.001
Level 5	14.7	11.9	−2.8	<.001	1.3	1.3	0.0	1.000	10.0	8.6	−1.3	.001
Level 6	14.0	11.7	−2.3	<.001	1.4	1.6	0.2	.331	10.6	8.8	−1.8	<.001
Level 7	13.6	11.3	−2.2	<.001	1.4	1.8	0.4	.079	11.1	9.3	−1.7	<.001
Level 8	13.1	10.9	−2.1	<.001	1.7	1.8	0.1	.613	11.6	10.0	−1.6	.006
Level 9	12.9	10.4	−2.5	<.001	1.7	2.1	0.4	.076	11.7	10.6	−1.1	.017
Level 10	12.8	10.2	−2.6	<.001	1.8	2.1	0.3	.217	11.7	11.0	−0.7	.149

ML, mediolateral; *AP*, anteroposterior; *IM*, intramedullar; *diff.*, difference.

Table V
Height correlation with intramedullar diameter and anteroposterior distance.

Correlation of height with humerus measures				
Level	IM diameter		ML-AP diameter difference	
	ρ	P value	ρ	P value
Level 1	0.566	<.001	−0.076	.453
Level 2	0.597	<.001	0.032	.751
Level 3	0.474	<.001	0.142	.159
Level 4	0.476	<.001	0.024	.813
Level 5	0.401	<.001	0.016	.875
Level 6	0.347	<.001	−0.069	.496
Level 7	0.366	<.001	−0.077	.448
Level 8	0.302	.002	−0.062	.541
Level 9	0.292	.003	−0.077	.449
Level 10	0.286	.082	−0.038	.820

IM, intramedullary; *AP*, anteroposterior.

postoperative alignment as compared to standard length stems.[12] A recent systematic review of short-stem RTSA noted only 7 studies commenting on alignment of the stem, with 18% noted to be malaligned in either valgus or varus.[23] It is worth noting that Humphrey and Bravman advocated for the use of a metaphyseal centering technique which prioritizes centering the humeral head within the metaphysis first and positioning within the diaphysis second.[17] They reasoned that in some cases short stems may be malaligned but well-fixated regardless. Stem length is an area of active research with regards to implant design and performance. Standard length stems were sized to extend 33% of the diaphysis and were traditionally used with good performance and survivorship.[19,21] By utilizing a stem which extends to the cylindrical section of the diaphysis (the TP), the implant stability is increased and the standard length stem reduces the risk of malalignment as reported with short-stem prostheses.[1,9] This reduction in malalignment could be achieved with a short-stem prosthesis which also extended beyond the TP described in this study.

The contribution of stem length to maintaining neutral alignment, and in the revision setting, achieving diaphyseal fixation for stability is of significant concern to the practicing orthopedic surgeon. Diaz et al conducted a biomechanical study to evaluate the contribution of stem length on initial implant fixation in RTSA.[11] Short- and long-stem lengths demonstrated equal initial fixation to allow bony on-growth in biomechanical testing. However, when initial fixation is inadequate clinically, stem subsidence has been demonstrated. Tross et al found a >5 mm subsidence in 11% of cases with short-stem RTSA in a retrospective comparative study with a minimum 12-month follow-up.[23] Long-term implications of stem subsidence in short-stem RTSA implants on clinical outcome or complications remain unknown. Authors have reported short-stemmed implants (size, 60-65 mm) to perform with comparable patient reported outcomes and range of motion compared to standard length with similar postoperative alignment, radiographic signs of loosening, and survival free of revision at short-term follow-up.[12,24] However, mid- and long-term follow-ups of short-stem RTSA data remain scarce. Although uncommon, short stems exhibit a higher stress level at the metaphysis increasing the risk of fracture in that region.[14] An analysis of this data suggests that the utilization of a short-stemmed implant of 70 mm which passes the TP would allow metaphyseal and diaphyseal fixation while decreasing the likelihood of malalignment and loosening; however, there would be an increased risk for periprosthetic fractures in both locations due to possible cortical weakening from the stress riser effect.[14] This risk with short stems slightly surpassing the TP has yet to be proven clinically. In the revision setting a stem of 76 mm would achieve fixation in the proximal diaphysis, whereas, a stem of 153 mm would achieve fixation in the mid diaphysis. Optimizing short-stem length with adequate engagement of the diaphysis at a key TP may help maximize sustainable benefits of short-stem arthroplasty.

This study is not without limitations. The measurements were limited to imaging, and thus are not clinically validated. Biomechanical testing would be helpful in validating if stem length extending past the TP decreases loosening as theoretically expected. Measurements did not consider the humeral canal curvature due to the limitations of the imaging modalities used. Measurement implications are limited to press-fit stems, not cemented or stemless designs in this study. This study did not account for interobserver analysis and the sample was conventional, and thus may not be generalizable to the general population.

Conclusion

This investigation demonstrated that humeral implants in reverse shoulder arthroplasty of at least 70 mm in length would reach past the TP in the majority of rotator cuff tear arthropathy cases regardless of sex. At this point, the canal's area is consistent in diameter and sphericity which would facilitate diaphyseal fixation for both male and female patients. This information should be investigated clinically as it displays the potential to maximize the purported benefits of short-stem arthroplasty implants including preservation of bone stock and ease of potential revision surgery while mitigating the risks of poor implant stability and the risk of malalignment.

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