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Glenoid Bone Grafting During Primary Reverse Shoulder Arthroplasty

A Learning-Curve Analysis

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Background: Reverse shoulder arthroplasty (RSA) with structural bone grafting of the glenoid utilizing an autograft from the resected humeral head is an effective strategy to address severe glenoid bone loss. Although learning curves have been established for RSA, RSA with bone grafting is more technically challenging, with relatively higher complication rates. The number of cases needed for proficiency and the optimal learning strategies have yet to be defined for RSA with bone grafting.

Methods: All patients who underwent primary, single-stage RSA with bone grafting for severe glenoid bone loss at our institution between November 2018 and February 2022 were identified. Perioperative data, including imaging, operative time, complications, revisions, postoperative functional data, and patient-reported outcomes, were recorded and analyzed. The learning curve for a fellowship-trained shoulder and elbow surgeon was analyzed using linear regression and cumulative sum (CUSUM) analysis. CUSUM analysis objectively evaluated differences in operative time over the course of the surgeon's practice and elucidated the completion of the learning curve.

Results: A total of 32 patients (53% male and 47% female; mean age, 68 years) were included in the analysis. The mean follow-up was 28 months. The mean operative time was 127 minutes, and there was a linear decrease in operative time throughout the study. CUSUM analysis using operative times demonstrated that the surgeon's learning curve was 14 patients. When comparing patients among the first 14 cases and the last 18 cases, there was no difference in shoulder range of motion, American Shoulder and Elbow Surgeons (ASES) scores, and Subjective Shoulder Value (SSV), while visual analog scale (VAS) pain scores at the time of final follow-up were better for patients in the surgeon's proficiency phase compared with the learning phase.

Conclusions: In this study, we found a significant linear decrease in operative time with the number of cases completed, without associated detriment to the postoperative outcome or complication rate. Our findings suggest that at least 14 cases may be required before proficiency is obtained with RSA using humeral head bone graft.

Level of Evidence: Prognostic Level IV. See Instructions for Authors for a complete description of levels of evidence.

Shoulder arthroplasty has been increasing at exponential rates, particularly due to the rise of reverse shoulder arthroplasty (RSA)[1,2]. Augmentation of RSA with structural glenoid bone grafting with the glenoid baseplate can help to correct glenoid version and inclination in the setting of massive glenoid bone loss, while also lateralizing the center of rotation to improve peripheral osseous impingement. This improves deltoid tensioning, increases impingement-free range of motion, and reduces scapular notching[3-6]. Utilizing a structural autograft from the resected humeral head accomplishes these goals and yields durable incorporation and deformity correction[3,7]. Indeed, clinically, it has yielded excellent functional outcomes, low revision rates, low notching rates, and good patient satisfaction[4-6,8-10].

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Some studies have presented concerns of graft resorption, baseplate loosening, and increased operative time[11]. Additionally, the autograft technique is limited to the index arthroplasty only[12]. Collectively, this has led some surgeons to propose the use of augmented metal baseplates when possible[11-14]. However, severe glenoid bone loss is challenging, and glenoid bone grafting remains an important solution. Furthermore, there is likely an association between surgeon experience and postoperative outcomes when performing glenoid bone grafting. Thus, it is reasonable to postulate that, with time and repetition, a trend of improvement in outcomes and operative times may be observed.

Surgeon experience has been reported as an important predictor of a successful outcome for patients undergoing RSA[15]. Kempton et al. described a drop in complication rates after performing 40 RSAs[16]. More recently, a shorter learning curve, whereby the complication rate and operative time diminished after 15 RSAs, was reported[17]. Due to the increased complexity, surgical steps, and nuances associated with glenoid bone grafting, the learning curve for this procedure may be longer even among surgeons who are already proficient in shoulder arthroplasty not requiring bone grafting.

A critical understanding of the indications and a meticulous surgical technique are imperative to the execution of glenoid bone grafting, as there are limited options in the setting of failure[18]. Determining when a surgeon is ready to independently perform RSA with bone grafting, and how proficiency can be accelerated, is important to the judicious use of health-care resources and patient-outcome optimization. However, the learning curve for RSA requiring structural bone grafting has not yet been defined. The purpose of the present study was to establish a learning curve for RSA with bone grafting, including the integration of observed trends in operative time, functional outcomes, and complication rates. We hypothesized that increased surgeon experience would be associated with decreased operative time, improved functional outcomes, and reduced complication rates.

Materials and Methods

Study Design

Following institutional review board approval, we performed a retrospective analysis of individuals who underwent primary RSA with structural bone grafting with an autograft from the humeral head. Our institution's surgical database was queried to identify all patients who underwent primary RSA with bone grafting between November 2018 and February 2022. All procedures were performed consecutively by 1 fellowship-trained shoulder and elbow orthopaedic surgeon at our institution. Patients were indicated for the glenoid bone-grafting procedure in the setting of severe glenoid bone loss to correct version or inclination, which was deemed by the senior author to be too severe to be accomplished with a standard metal augment (Table I). Patients undergoing revision procedures or planned 2-stage arthroplasty procedures were excluded.

Basic demographic information, perioperative clinical data, and imaging data were collected. Intraoperative data included operative time from incision to closure and intraoperative complications. Postoperative data included complication rates, reoperations, range of motion, and subjective patient-reported outcomes (PROs), including the American Shoulder and Elbow Surgeons (ASES) score, Subjective Shoulder Value (SSV), and visual analog scale (VAS) pain score. Active range of motion, including forward flexion, abduction, external rotation, and internal rotation, was assessed at the time of final follow-up using the Constant-Murley scale[19]. Range of motion was assessed and measured by a fellowship-trained shoulder surgeon. Individuals with <2 years of follow-up in the electronic medical record were contacted via telephone to obtain complete data.

TABLE I Author Indications for Glenoid Bone Grafting to Correct Version or Inclination Based on the Preoperative Planning Software Using Preoperative CT Imaging

(1) Version correction to within 5°-10° of native version could not be obtained by off-the-shelf metal augments

(2) Inadequate glenoid bone stock:

- In width (<15 mm)
- Medialized relative to the coracoid, or
- Dysplastic (Walch C)

Surgical Technique

All procedures were performed consecutively by the senior author (E.R.W.). All cases were preoperatively templated with software using the preoperative computed tomography (CT) imaging, and preoperative version and inclination were calculated using previously described methods[20-22]. The bone graft was used to attempt to correct retroversion or superior inclination deformity to <5° from neutral retroversion or <5° from the RSA angle[20]. No patient-specific instrumentation was utilized in this series. Our technique for RSA with structural glenoid bone grafting using a humeral head autograft has been previously described[23] and comprises placement of a wedge-shaped autograft on a baseplate with a long central post (Fig. 1).

Statistical Analysis

All statistical analyses were performed using SPSS Statistics (version 29.0; IBM). The data were tested for normality using a Shapiro-Wilk test. Categorical data were analyzed with Fisher exact tests, and continuous data were analyzed with independent sample t tests and Mann-Whitney U tests. Linear regression analysis was utilized to assess the relationship between operative time and case number over the course of the procedures performed by the surgeon. All tests were 2-sided, and p values of <0.05 were considered significant.

Cumulative sum (CUSUM) analysis was adopted to quantitatively evaluate the learning curve, similarly to previous studies[24,25]. The point at which the surgeon had completed the learning curve was determined by the maximum CUSUM of all cases.

Results

A total of 36 consecutive RSAs requiring structural bone grafting were performed by a single surgeon during the

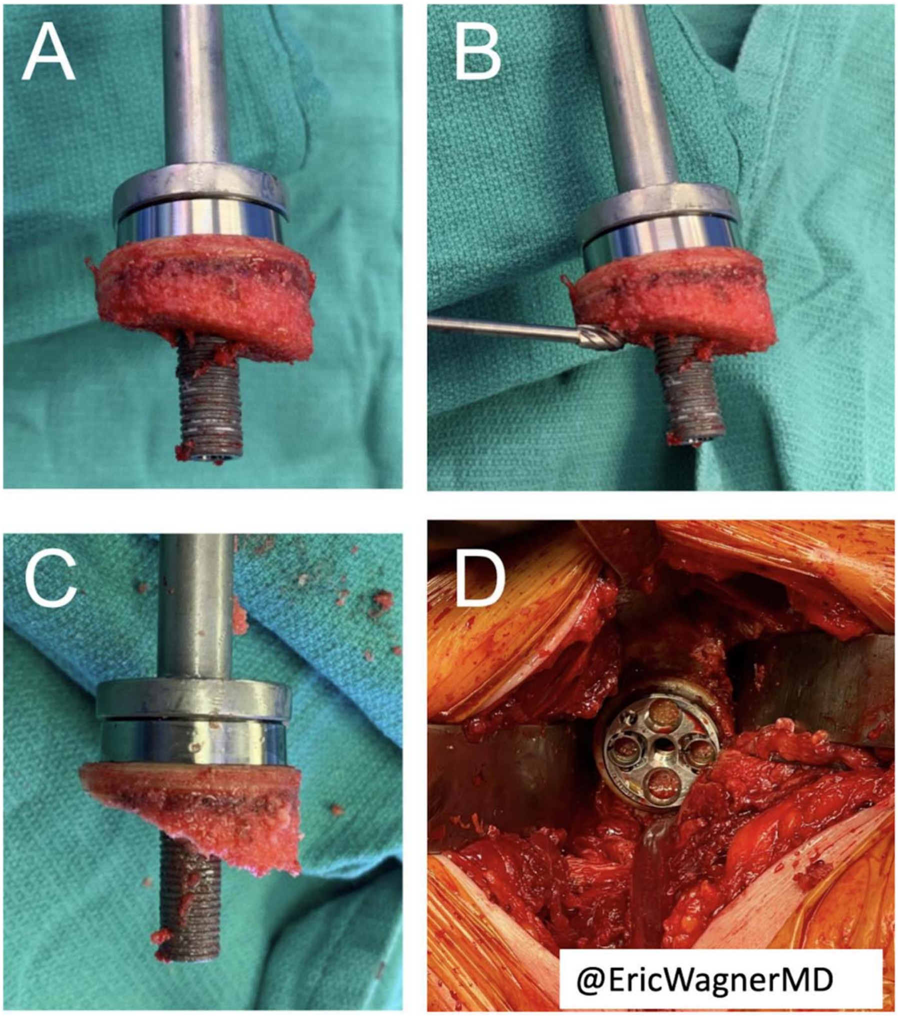

Fig. 1

Clinical intraoperative photographs showing a humeral head autograft wedge used with reverse shoulder arthroplasty (RSA) to address posterior or superior glenoid bone loss. The graft is placed behind the baseplate over a large glenoid post (**Fig. 1-A**). A burr is used to shave the graft (**Fig. 1-B**), to fit the defect and produce an angled graft (**Fig. 1-C**). The larger side of the graft is positioned into the defect after reaming, correcting the deformity (**Fig. 1-D**).

study period. Of these, 4 shoulders were excluded because of concomitant lower-trapezius tendon transfer (2 shoulders), revision surgery (1 shoulder), and a procedure separated into 2 stages (1 shoulder), leaving 32 shoulders (32 patients) available for analysis. Demographic, clinical, and imaging characteristics are shown in Table II. The mean patient age was 68 years (range, 48 to 78 years). When stratified by case number, the groups had similar characteristics.

Outcomes

Complete outcome data are shown in Table III. For the entire cohort, the mean operative time, from incision to closure, was 127 minutes. At the time of final follow-up, mean forward flexion was 149°, abduction was 131°, and external rotation was 53°. When evaluating PROs, mean values for the ASES score, SSV, and VAS pain score were 79.9, 88.0%, and 1.1, respectively. CT scans were obtained between 2 and 7 months postoperatively for 23 (72%) of the 32 patients, and among those with CT, all cases (100%) demonstrated complete graft incorporation without evidence of nonunion.

Subgroup Comparison Based on Case Number

Linear regression analysis assessing temporal changes in operative time showed a significant decrease in operative time as cumulative case volume increased ($R = -0.785$; $R^2 = 0.574$; $p < 0.001$) (Fig. 2). The CUSUM curve for operative time is shown in Figure 3. The CUSUM analysis demonstrated completion of the surgeon's learning curve after 14 cases. The remaining 18 cases demonstrate the surgeon's proficiency phase.

A comparison of the first 14 cases (before completion of the learning curve) and the last 18 cases (the surgeon's

TABLE II Demographic, Clinical, and Imaging Characteristics of Patients Undergoing RSA with Bone Grafting*

		Cases		
	Overall (N = 32)	1-14 (N = 14)	15-32 (N = 18)	P Value
Age *(yr)*	68.16 ± 6.27	69.14 ± 2.93	67.39 ± 7.99	0.399
Sex				0.308
Male	17 (53.1)	9 (64.3)	8 (44.4)	
Female	15 (46.9)	5 (35.7)	10 (55.6)	
Laterality				1.00
Left	12 (37.5)	5 (35.7)	7 (38.9)	
Right	20 (62.5)	9 (64.3)	11 (61.1)	
BMI *(kg/m²)*	28.77 ± 4.52	28.31 ± 3.79	29.13 ± 5.10	0.604
Smoking status				0.459
Never	20 (62.5)	9 (64.3)	11 (61.1)	
Current	11 (34.4)	4 (28.6)	7 (38.9)	
Former	1 (3.1)	1 (7.1)	0 (0.0)	
Diabetes	5 (15.6)	1 (7.1)	4 (22.2)	0.355
Osteoarthritis	22	11	11	
Rotator cuff arthropathy†	10	2	8	
Walch classification				
A2	2	2	0	
B2	3	2	1	
B3	15	7	8	
C	1	0	1	
D	1	1	0	
Inclination	11.6°	11.2°	11.8°	0.764
Version	23.2°	26.1°	20.8°	0.357

*The values are given as the mean ± standard deviation, or as the number with the percentage in parentheses. RSA = reverse shoulder arthroplasty, and BMI = body mass index. †For all of these patients, rotator cuff arthropathy was classified as Hamada stage 5 with extensive bone loss.

proficiency phase) showed a significant decrease in the mean operative time by 42 minutes (from 151 for the learning phase to 109 minutes for the proficiency phase; $p < 0.001$). At final follow-up, the mean VAS pain score was also significantly lower for patients who underwent RSA with bone grafting in the proficiency phase compared with the learning phase (0.50 versus 1.92; $p = 0.046$) (Fig. 4). The mean postoperative ASES score ($p = 0.514$) and SSV ($p = 0.694$) did not differ significantly between patients whose cases were in the learning phase compared with the proficiency phase. Similarly, no differences were observed in final range of motion between patients operated on in the learning phase versus proficiency phase. To limit case complexity as a potential confounding variable, preoperative glenoid inclination and version were measured and showed no differences between phases (Fig. 5, Table II). Of note, the mean follow-up time (and standard deviation) for patients who were among the first 14 cases was significantly greater than for those who were among the last 18 (40.20 ± 8.22 versus 18.84 ± 4.68 months; $p < 0.001$); however, this is to be expected, as the latter group consisted of patients with more recent procedures. Postoperative radiographic images following RSA with bone grafting are shown in Figure 6 and Video 1.

Complications

One postoperative complication was reported. The seventeenth patient in the series developed a shoulder hematoma 2 weeks following their procedure. It was successfully treated with irrigation and debridement, and intraoperative culture results were negative.

There were no reoperations performed in the postoperative period.

Discussion

Structural bone grafting of the glenoid with a humeral head autograft in RSA is an effective strategy to address glenoid bone loss, decrease impingement, and improve shoulder motion, strength, and stability[3-5,10,26-33]. Although learning curves

TABLE III Outcome Data of Patients Undergoing RSA with Bone Grafting*

		Cases		
	Overall (N = 32)	1-14 (N = 14)	15-32 (N = 18)	P Value†
Operative time *(min)*	127.03 ± 29.58	150.79 ± 22.86	108.56 ± 19.22	**<0.001**
Cases 1-5 *(min)*	158.20			
Cases 28-32 *(min)*	91.80			
ASES score	79.94 ± 16.37	80.38 ± 18.40	79.61 ± 15.31	0.514
SSV *(%)*	88.03 ± 11.54	88.71 ± 12.86	87.50 ± 10.74	0.694
VAS pain score (0-10)	1.10 ± 1.83	1.92 ± 2.29	0.50 ± 1.15	**0.046**
Range of motion				
Flexion *(deg)*	148.75 ± 30.98	147.50 ± 34.07	149.72 ± 29.33	0.639
Abduction *(deg)*	130.78 ± 28.03	132.14 ± 29.72	129.72 ± 27.47	0.398
External rotation *(deg)*	53.31 ± 18.61	56.43 ± 17.81	50.89 ± 19.36	0.398
Internal rotation *(no. of spine levels)*	6.71 ± 3.21	7.57 ± 2.85	6.00 ± 3.39	0.246
Follow-up *(mo)*	28.18 ± 12.50	40.20 ± 8.22	18.84 ± 4.68	**<0.001**

*The values are given as the mean with or without the standard deviation. RSA = reverse shoulder arthroplasty, ASES = American Shoulder and Elbow Surgeons, SSV = Subjective Shoulder Value, and VAS = visual analog scale. †Significant values are in bold.

have been established for RSA, RSA with bone grafting is more technically challenging, with relatively higher complication rates. Despite a well-established learning curve for RSA, the learning curve for the more technically demanding RSA with bone grafting has yet to be defined; doing so may help optimize outcomes and efficiency.

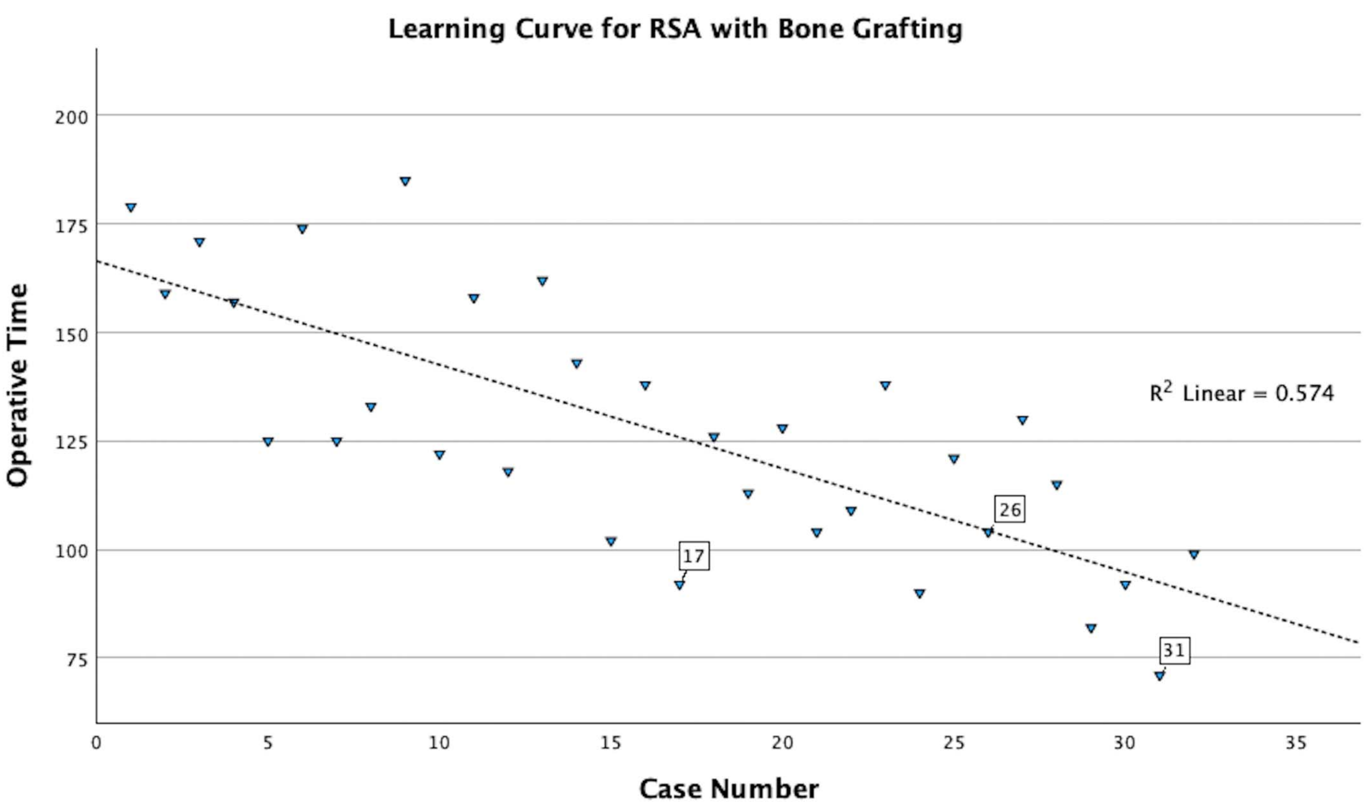

Fig. 2

Scatterplot for operative time ($R^2 = 0.574$). The dashed line represents the line of best fit. Numbered data points reflect the case numbers of patients with postoperative complications. RSA = reverse shoulder arthroplasty.

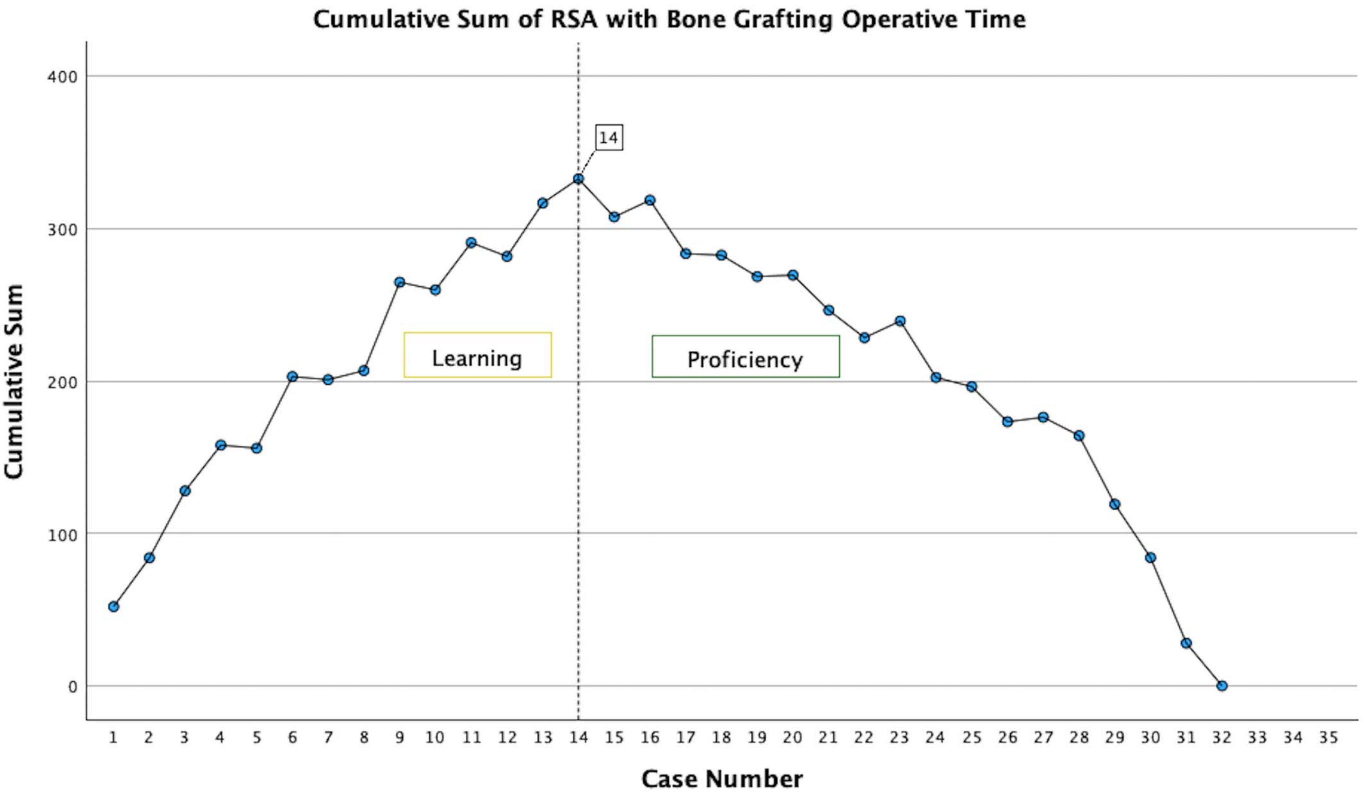

Fig. 3
Cumulative sum (CUSUM) curve for operative time, with the mean operative time as the target. Point 14 is the case with the highest CUSUM value, and the dashed line reflects the end of the learning phase and start of the proficiency phase. RSA = reverse shoulder arthroplasty.

In this study, we evaluated 32 consecutive patients who underwent RSA with bone grafting with humeral head autograft and found a significant inverse relationship between the number of cases completed and operative time. The mean VAS pain score at the time of final follow-up was significantly lower for the cohort who underwent the procedure during the surgeon's proficiency phase. No relationship was found between the number of cases completed and functional clinical outcomes or complication rates. Our findings suggest that surgical proficiency with RSA with bone grafting improves with surgical experience, without an associated learning curve impacting outcomes or complications. Furthermore, according to our findings, the learning phase is during the first 14 procedures performed by a fellowship-trained shoulder and elbow surgeon. After this, when the surgeon enters their proficiency phase, a decrease in operative time can be expected without associated detriment to postoperative outcomes or complication rates.

Operative time is a simple, albeit imperfect, surrogate for surgeon and team proficiency[34], assuming that the same surgical steps have been replicated in all cases and the pathologies being treated are similar. Shorter operative time has many benefits[35], including reduced exposure to anesthesia, reduced blood loss[36], lower infection risk[35,37], and lower incidence of wound dehiscence[35,36,38]. Multiple studies have reported that surgical experience is associated with reduced operative times in shoulder arthroplasty[35,39-41]. Similarly, in the arthroscopy literature, negative outcomes have been associated with increased operative time in shoulder surgery, including higher superficial surgical site infection risk and increased risk of overnight hospital stay[42,43]. In the current study on RSA with bone grafting, the learning curve for operative time was 14 procedures. Our results are similar to the learning curve for RSA, 15 shoulders, reported by Choi et al. for indications of cuff tear arthropathy, massive irreparable tears, and osteoarthritis[17]. Similarly, examining the learning curve in RSA for proximal humeral fractures, Blaas et al. found a learning effect of 20 procedures[24].

The specific strategies that we believe can accelerate the surgical learning curve are shown in Table IV. Particular emphasis should be placed on employing deliberate practice via templating, planning and instrumentation, communicating with the team, and using video to critically evaluate inefficiencies and improve performance[44,45]. Indeed, video learning before and after each case could potentially lead to rapid skill acquisition[46]. Intraoperative video recording also offers the opportunity for teaching and asking a peer mentor for technical critique[46]. Effective teamwork from the circulator, scrub technician, and surgical assistant is critical to overall success, and team training and improving procedure familiarity could expedite team proficiency. Bone grafting with RSA is one of the

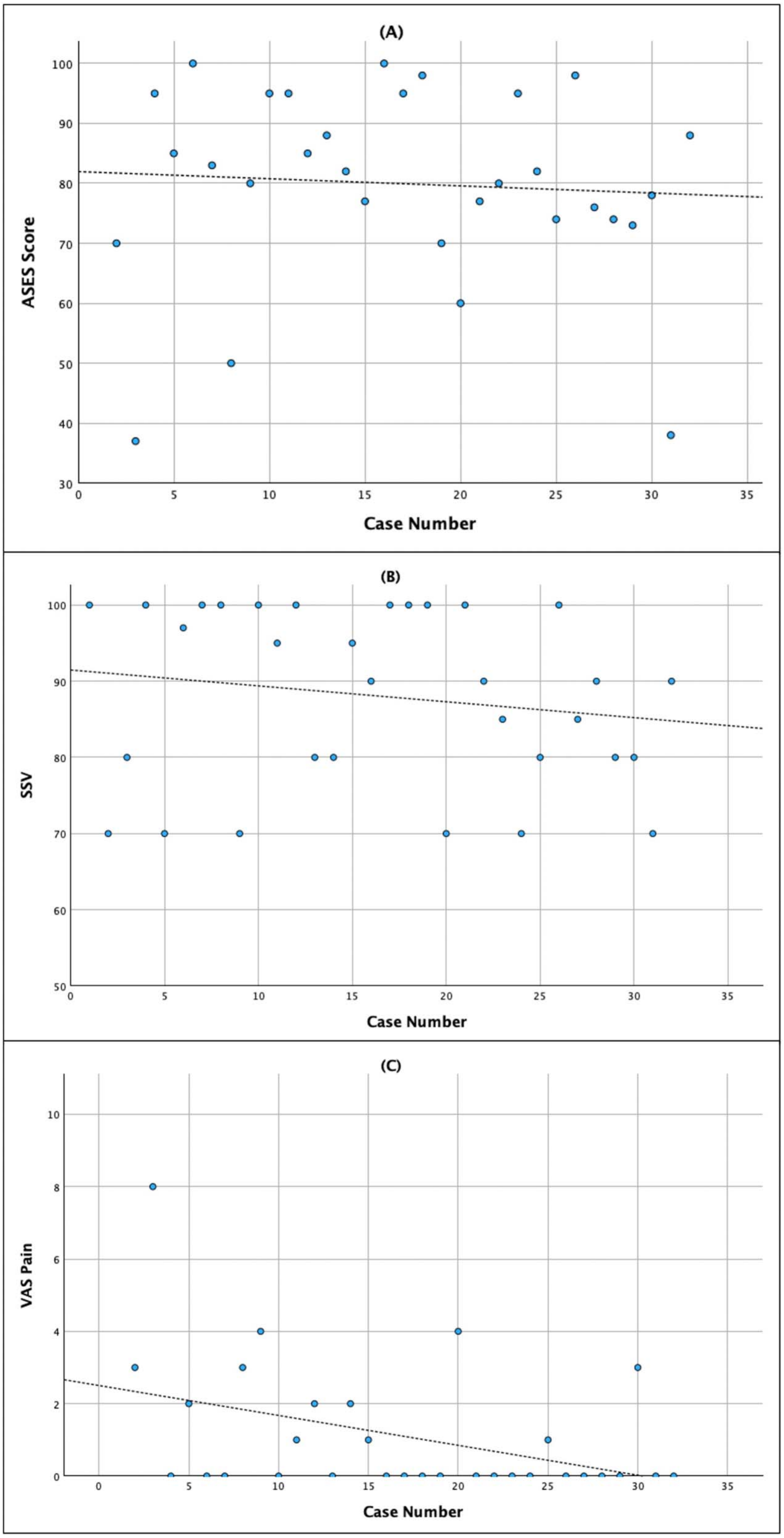

Fig. 4

Scatterplots for the patient-reported outcomes of the American Shoulder and Elbow Surgeons (ASES) score (R^2 = 0.004) (**Fig. 4-A**), Subjective Shoulder Value (SSV) (R^2 = 0.029) (**Fig. 4-B**), and visual analog scale (VAS) pain score (R^2 = 0.168) (**Fig. 4-C**). The dashed lines represent the line of best fit.

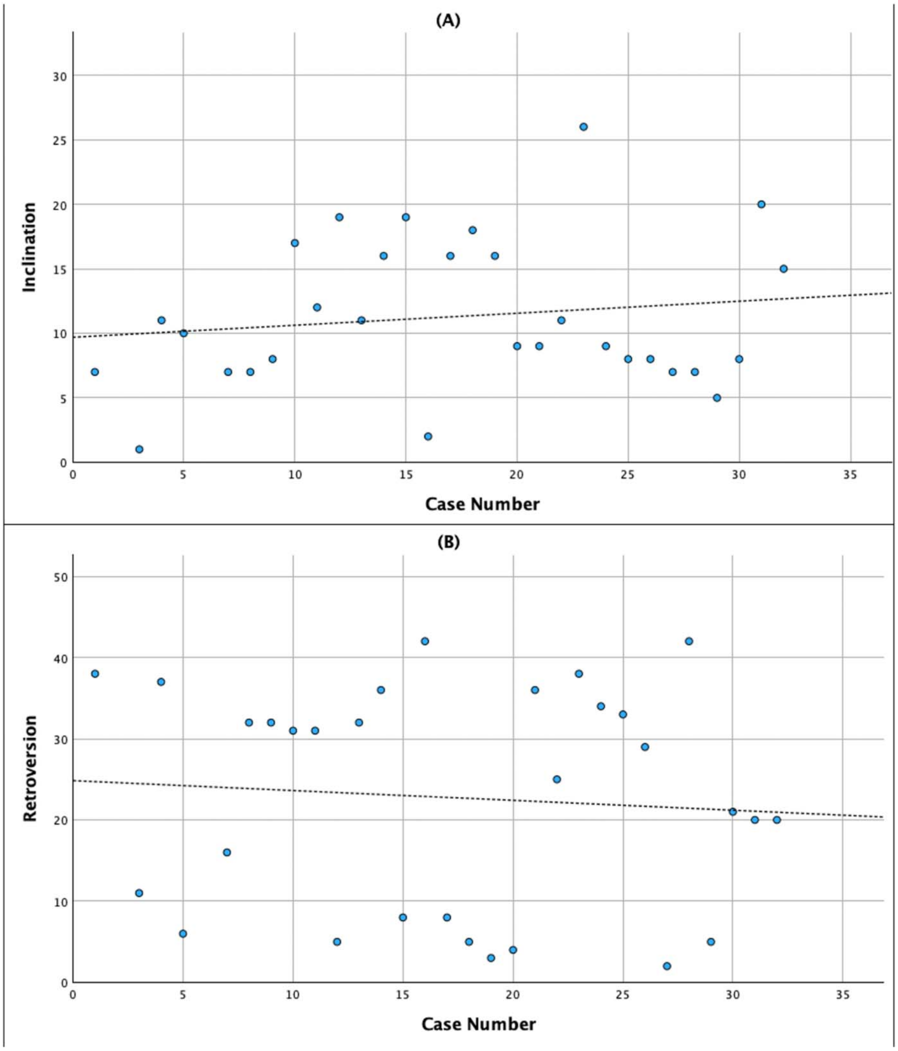

Fig. 5

Scatterplots for shoulder superior inclination ($R^2 = 0.006$) (**Fig. 5-A**) and retroversion ($R^2 = 0.014$) (**Fig. 5-B**). The dashed lines represent the line of best fit. Case complexity did not significantly differ between the learning and proficiency phases.

more complex procedures a shoulder surgeon performs, and proficiency with shoulder arthroplasty in settings of complex bone loss is becoming increasingly important in both the primary and revision settings; as the indications for RSA continue to expand, the use of prostheses increases and more time passes since they were first introduced[1,2].

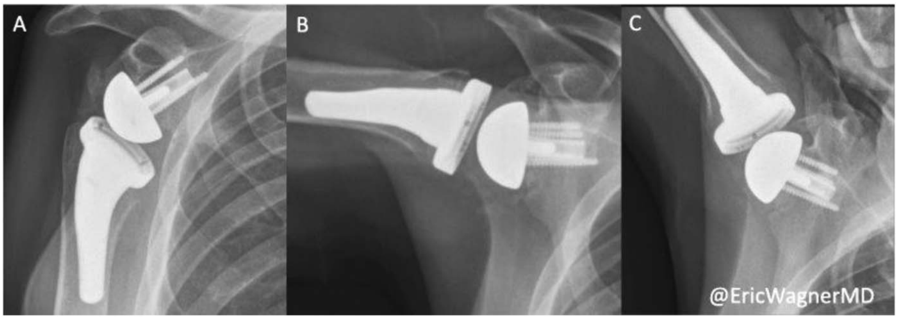

Fig. 6

Postoperative digital dynamic Grashey radiographs following reverse shoulder arthroplasty with an angled humeral head bone graft. Images taken at rest (**Fig. 6-A**), at 90° of humerothoracic abduction (**Fig. 6-B**), and at 130° of humerothoracic abduction (**Fig. 6-C**).

TABLE IV Recommendations to Shorten the Learning Curve and Optimize Surgical Efficiency for Glenoid Bone Grafting

Preoperative	Templating with software to measure the graft and for exact positioning
	Operating room (OR) staff familiarity with instrumentation
	Communicating the operative plan with the team
	Active learning using lessons from prior surgeries to optimize future surgeries
Intraoperative	Burr to shape the graft according to the preoperative template
	Use a saw to shave the initial part of the graft, then prepare with a reamer prior to humeral head cut
	Use preoperative templating to guide central pin insertion, then right angle grasper around the front of the glenoid to confirm version of the pin positioning
	Record intraoperative video footage, e.g., with a head-mounted camera, to evaluate technique
Postoperative	Document personal case reflections and use them for better performance in the next case
	Critically evaluate radiographs to create a personal feedback loop
	Review intraoperative video and critically evaluate mistakes and inefficiencies
	Incorporate active learning into future cases to optimize efficiencies
	Regular and effective intraoperative and postoperative communication with the OR team

While some may propose that procedural quality is compromised in the effort to achieve shorter operative times, our results did not show any worsening of postoperative functional outcomes as operative times decreased. In addition, better VAS pain scores at final follow-up were found for patients who underwent procedures in the proficiency phase compared with the learning phase. The exact reason for the mean VAS pain score being lower is unclear, but it is possible that these patients had lower baseline pain levels or more accurate surgical expectations, or that soft-tissue tensioning and implant placement were improved after learning from prior cases. Our clinical outcomes are consistent overall with those of prior analyses of RSA with structural bone grafting using a humeral head autograft that employed the same instrumentation: a ring of bone around the central long post or screw that was taken from the humeral head[47,48]. In a meta-analysis, pooling 235 RSAs with bone grafting from 8 studies, good outcome scores were reported, with good rates of graft healing and range of motion that was equivalent to that of standard RSA[49].

We also found no corresponding increase in complications with decreasing operative time. We report only 1 complication, an aseptic hematoma at 2 weeks postoperatively. There were no cases of symptomatic baseplate loosening or bone-graft nonunion, which have been reported by other authors[12]. Additionally, after grafting with humeral head autograft and iliac crest autograft during primary RSA, Wagner et al. reported that transient neurapraxias were the most common complication[6], which we did not observe. Of note, Choi et al. also analyzed the learning curve on the basis of complications and found the total complication rate to be 16% (6 of 38 patients; 2 intraoperative and 4 postoperative complications), and all complications occurred in the first 20 procedures[17]. The complications included arterial injury, axillary nerve palsy, periprosthetic humeral fracture, acromion fracture, glenoid fracture, and superficial infection. Although the complication that we report was after case 14, in the proficiency phase, this did not have long-term effects, and this type of complication is likely to still occur despite the surgeon being more proficient.

While the current study focused on optimizing glenoid bone-grafting proficiency as a solution for glenoid bone loss with deformity, using custom implants and patient-specific instrumentation also are effective solutions[50-52]. However, we prefer not using patient-specific instrumentation because of the increased cost and time needed for manufacturing and delivering the guide after planning. Furthermore, cases in which these implants fail to achieve adequate fixation to the remnant glenoid are often associated with notable scapular pathologies that are very difficult to address by way of revision or salvage. We also prefer using bone grafting for severe glenoid deformities that no off-the-shelf metal augment can correct, especially for large, uncontained defects, because of the high complication rate (recently reported to be 29%) and the lack of long-term data on patient-matched glenoid implants[51].

This study had limitations. First, as a retrospective case series, there was limited follow-up of our patient population, and further longitudinal analysis could capture any delayed complications and reduce the impact of the different follow-up durations for early and late cases, which was a consequence of the study design. Additionally, we have incomplete data on incorporation rates, with 23 (72%) of 32 having a postoperative CT scan, and therefore, while the 100% incorporation rate in the group who did undergo CT scanning is reassuring, we cannot extrapolate this to the whole sample. We have adopted operative time as a surrogate for surgeon and team proficiency; however, this metric does not take into account case complexity, as has been done in the general surgery literature[53]. However, by examining complication and reoperation rates, we have indirectly accounted for this. Our outcomes have not been demonstrated with other instrumentation techniques using humeral head autograft, and our data may not be generalizable[27,54-56]. In addition, this series reflects procedures performed by a single, fellowship-trained shoulder and elbow surgeon, operating in a complex shoulder tertiary referral practice, who was already proficient in total shoulder arthroplasty not requiring bone grafting; the learning curve of this surgeon is not necessarily generalizable outside of that setting, particularly to novice surgeons. Future studies should include more surgeons, more detailed metrics of case complexity that can be controlled for, a detailed imaging analysis that is more sensitive to complications, and the use of other metrics of intraoperative proficiency, such as video footage rated by surgeon peers. Finally, race and ethnicity data of patients were not available, a limitation of this study.

In summary, this study found a significant linear relationship between the number of cases completed and decreasing operative time, without associated detriment to the postoperative outcome or complication rate. Our findings suggest that surgical proficiency with glenoid bone grafting in primary RSA for severe glenoid bone loss improves with surgical experience during the learning phase of 14 procedures. This learning-curve analysis provides important information for future studies on optimizing procedures for severe glenoid bone loss. ■

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