Techniques in Shoulder and Elbow Surgery 6(2):57–66, 2005

TECHNIQUE

Shoulder Arthroplasty for Fracture: Restoration of the "Gothic Arch"

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ABSTRACT

Shoulder arthroplasty for fracture remains a technically challenging procedure, often with unpredictable clinical outcomes in the reported literature. Consequently, the appropriate management of certain 3- and 4-part fractures and fracture-dislocations of the proximal humerus remains controversial. However, recent advances in our understanding of the intraoperative technical pitfalls with shoulder fracture arthroplasty have created the potential for more reproducible functional results. Restoration of the "gothic arch" of the shoulder girdle combined with anatomic tuberosity reconstruction can make this operative procedure reproducible.

HISTORICAL PERSPECTIVE

In 1951, Charles Neer first proposed treating displaced fractures of the proximal humerus by replacement of the fractured and devascularized cephalic fragment with a prosthesis[1] (Fig. 1). Two decades later Neer reported excellent or satisfactory results in approximately 90% of patients after prosthetic hemiarthroplasty for proximal humeral fracture.[2–4] Unfortunately, no other published study in the peer-reviewed literature has been able to match that outstanding mark. Most other authors have reported less satisfactory and even disappointing functional results, often with stiff and painful shoulders, demonstrating that shoulder replacement itself may not guarantee a successful outcome.[5–19] In light of this, some surgeons opt for conservative rather than surgical treatment of these difficult injuries.[20,21]

As Dr. Neer first highlighted, technical considerations may be implicated in these unpredictable results. Because of the infrequency of these fractures, a relative lack of experience of the treating orthopedic surgeon may create difficulties dealing with the intraoperative complexity of the injuries. Several authors have reported unpredictability with correctly positioning the prosthesis in both height and retroversion, due to the absence of accurate anatomic landmarks after fracture.[6,7,15] Furthermore, the associated problem of accurately restoring and fixing the displaced tuberosity fragments may also contribute to the reported incidences of tuberosity malunion, nonunion, and bone resorption. As previously reported, failure of the greater tuberosity to anatomically heal to the humeral shaft is the single most prevalent complication after fracture arthroplasty and is the single most important reason for poor functional outcomes in these cases.[6,7,22]

Our own clinical studies convinced us that our early reconstructions using a shoulder prosthesis were inadequate and unpredictable in displaced 4-part fractures of the proximal humerus.[6,7] To this end, ancillary fracture-specific instrumentation has been developed in an attempt to reduce the subjective variables associated with intraoperative prosthetic positioning[6,7,23] (Fig. 2). However, in many surgical cases, the operating surgeon may not have access to a fracture "jig" at the time of the operation. In light of this, we have concentrated our efforts on developing a simple and reproducible technique for anatomic proximal humeral reconstruction: restoration of the "gothic arch" of the proximal shoulder girdle with stable tuberosity osteosynthesis during fracture arthroplasty.

INDICATIONS AND CONTRAINDICATIONS

Proximal humeral hemiarthroplasty is indicated for most patients with 4-part fractures, displaced 3-part fractures, fracture-dislocations, and head splitting fractures of the proximal humerus—especially in elderly patients with

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FIGURE 1. Displaced 4-part proximal humerus fracture.

FIGURE 2. Fracture "jig" instrumentation (Aequalis Fracture System, Tornier, St. Ismier, France).

low to moderate physical demands. Bone quality is not a contraindication to prosthetic implantation, although osteoporotic bone increases the difficulty of the tuberosity reconstruction. Most authors have previously advocated operative treatment as soon as possible after injury (even within 24 hours) depending on the medical stability of the patient. However, based on the often impressive soft tissue swelling and hematoma that accompany these injuries, we conversely feel that optimal surgical timing for shoulder fracture arthroplasty is approximately 6–10 days after injury to allow for resolution of this significant shoulder girdle soft tissue swelling (assuming no acute neurovascular injury or compromise that would necessitate earlier intervention). Longer periods of time (usually longer than 20 days) between injury and surgery do not preclude the implantation of a prosthesis, but both intraoperative difficulty with anatomic reconstruction as well as postoperative functional outcome do appear to be negatively compromised in such situations.

Contraindications to shoulder fracture arthroplasty usually involve medical comorbidities that prevent surgical management in general. Patients with such medical issues, extremely low functional demands in their shoulder, and no pain at the time of presentation may best be considered for conservative measures. The appropriate decision-making algorithm between fracture osteosynthesis and fracture arthroplasty is beyond the scope of this manuscript, but selected younger patients or patients with valgus-impacted 4-part fractures should at least be considered for osteosynthesis of the fracture (either percutaneous or open) instead of arthroplasty.

The very rare patient who both suffers a fracture and also has either preexisting glenohumeral arthritis or irreparable rotator cuff tearing is not a contraindication to conventional shoulder fracture arthroplasty. However, the implantation of a glenoid prosthesis at the time of proximal humeral replacement should be undertaken if true glenohumeral arthrosis preexists. In cases with irreparable cuffs or cuff tear arthropathy and concomitant fracture, recently available reverse ball designs may be considered though the indications remain rare indeed.

■ PREOPERATIVE PLANNING

Preoperative planning and preparation are essential in shoulder fracture arthroplasty and begin at the initial evaluation. As most patients with displaced proximal humerus fractures are elderly, a detailed history for any coexisting injuries should involve an inquisition into any potential head trauma or reason for the usual fall that caused the injury. In addition to distal neurovascular appropriate evaluation, physical examination must pay special attention to the axillary nerve motor and sensory distribution—most of these patients appear to suffer some degree of axillary neuropraxia from the violence of the injury that may be detected by subtle dysesthesia or decreased firing in the middle and posterior deltoid regions. It is this neurologic compromise that likely prolongs the eventual time for true functional recovery of active overhead elevation after surgery (often 12–18 months after injury). Hence, preoperative counseling regarding the length of rehabilitation and recovery is essential for both patient and operating surgeon.

As indicated earlier, the timing of shoulder fracture arthroplasty does appear important to both reduction of wound complications as well as eventual recovery of function. Unless true vascular compromise is present, immediate surgery through edematous skin is avoided. The optimal time appears to be 6–10 days after injury, and most patients appear to tolerate this period with acceptable control of fracture pain. It does also appear, especially in the more elderly patients, that this period of time becomes more and more important for uncovering occult injuries that may have been initially overlooked and/or for stabilizing any medical comorbidities. In our experience, periods longer than 20 days increase the difficulty of intraoperative mobilization of the greater and lesser tuberosity fragments due to early fracture healing, and hence require more extensive soft tissue and bone dissection that may negatively impact eventual tuberosity healing.

Preoperative radiographic planning is paramount in reproducible shoulder fracture arthroplasty. We obtain full-length scaled X-rays of the injured and the contralateral humeri with a ruler of defined length. This can even be done in the operating room immediately prior to surgery and should not be overlooked (Fig. 3A and B). While surgeons in the past have subjectively ''eyeballed'' appropriate prosthetic position, this simple preparation will allow an easy, reproducible, and accurate restoration of proximal humeral anatomy.

■ SURGICAL TECHNIQUE

In a modified beach-chair position, with the scapula supported, a 2.5–3 inch deltopectoral approach is used. We have found that a well-placed incision and a mobile soft tissue window will permit the procedure to be performed easily through this limited incision (Fig. 4). With a self-retaining retractor holding the deltoid laterally and the conjoint tendon medially, a Hohman retractor is placed above the coracoacromial ligament and a curved retractor is placed above the acromion.

Manipulation of the tuberosity fragments should be kept to a minimum to preserve any intact periosteal attachments to the diaphysis. The long head of the biceps is then identified and tagged, and a tenotomy is performed for later soft-tissue tenodesis at the end of the procedure. Typically, the fracture line can be located with a blunt elevator or osteotome between the tuberosities, just posterior to the bicipital groove. The intertubercular fracture line is followed proximally through either the rotator interval or the rotator cuff medial to the level of the glenoid. It is important to follow the fracture line itself through the soft tissue of the rotator interval/rotator cuff as opposed to creating an ''iatrogenic'' separate fracture line. Any bleeding from the anterior humeral circumflex artery or its venae commitantes is controlled with electrocautery.

Four horizontal mattress heavy #5 Ethibond (Ethicon, a Johnson and Johnson Company, Norwood, MA) nonabsorbable sutures are placed around the greater tuberosity at the bone–tendon junction (2 in the

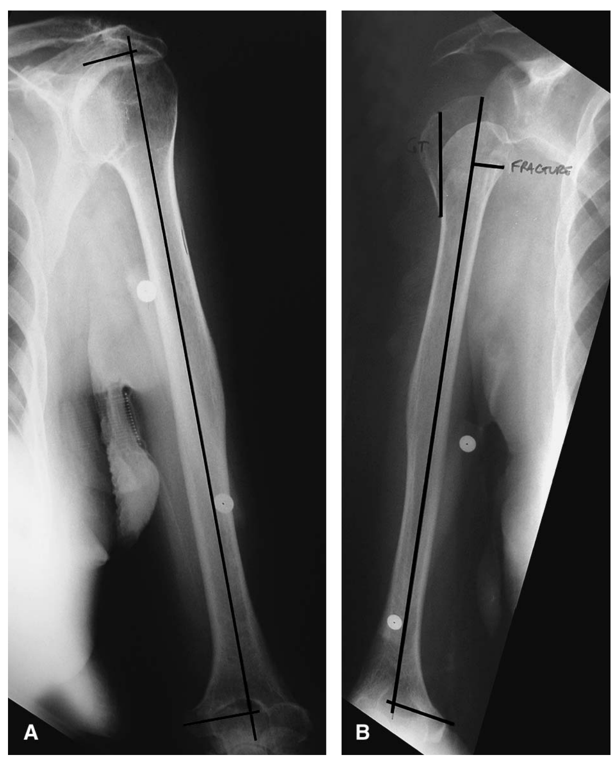


FIGURE 3. A, Scaled radiograph of normal humerus. B, Scaled radiograph of injured humerus.

FIGURE 4. Limited 3-inch modified deltopectoral incision used for shoulder fracture arthroplasty.

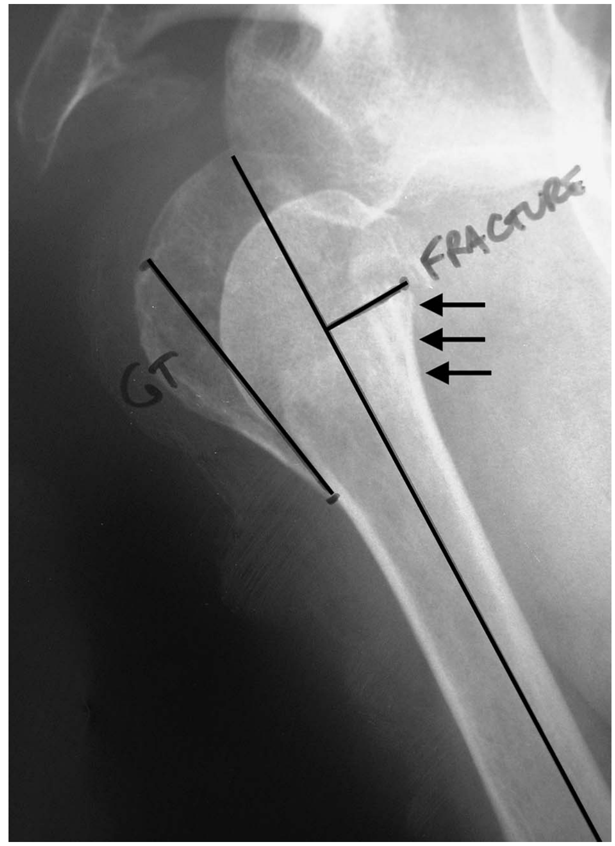


FIGURE 5. The medial "calcar" of the proximal humerus is the portion of the humeral shaft just below the inferior limit of the anatomic neck.

infraspinatus and 2 in the teres minor). Two temporary stay sutures are placed around the lesser tuberosity at the subscapularis/bone tendon junction. The tuberosities are gently retracted apart. The origin of the long head of the biceps is then excised from the supraglenoid tubercle, and the head fragment is removed and measured with a caliper. If the humeral head falls in between sizes, the smaller size is selected. Structural cancellous bone graft is procured from this articular fragment. Additionally, the glenoid is inspected for defects or significant erosion requiring replacement (exceedingly rare).

The medullary canal is prepared using cylindrical reamers and trial implants by hand of increasing diameter. Once the appropriate trial implant and head size are determined, retroversion is selected by facing the prosthetic head toward the glenoid with the forearm in neutral rotation at the side (approximately 20° of retroversion relative to the transepicondylar axis of the elbow). This position can be marked on the lateral cortical humeral shaft with either a marking pen or an electrocautery.

An Aequlis Fracture Stem (Tornier, St. Ismier, France) of the appropriate diameter is opened, and the pre-selected trial head is placed on this definitive implant with the eccentric head offset rotated into the most lateral position. This allows for the least amount of "medial overhang" of the humeral head during the all-important restoration of the "gothic arch."

The 4 Steps to Restoring the "Gothic Arch"

This technique differs from previously described techniques that reference the prosthetic humeral reconstruction off of the lateral portion of the humerus and humeral metadiaphysis. In most proximal humeral fractures, the medial "calcar" of the proximal humerus is intact; this "calcar" is the proximal medial humeral shaft just inferior to the anatomic neck (Fig. 5). In the few cases where the medial calcar is fractured, this fragment is often large and can be rigidly fixed with simple wire or heavy suture fixation. By referencing the reconstruction off of the medial calcar, the "gothic arch" can be objectively recreated in a methodical fashion.

The "gothic arch" is our term for the architectural anatomy of the proximal shoulder girdle. The arch is easily seen on a normal radiograph by tracing the medial border of the proximal humeral calcar to the articular surface and joining this with the lateral border of the scapula to the articular surface: joining these lines forms the classic "vaulted" or "gothic" arch shape seen in medieval period renaissance architecture (Fig. 6). The 4 steps (2 X-ray, 2 intraoperative) for restoration of this gothic arch provide a very reproducible restoration of humeral height and consequent potential for anatomic tuberosity reconstruction.

Step 1 (X-Ray): Fracture to Top of Head Height (Fig. 7A, B, C, and D)

Using the scaled X-rays, the entire length of the normal humerus (N) along a perpendicular from the medial

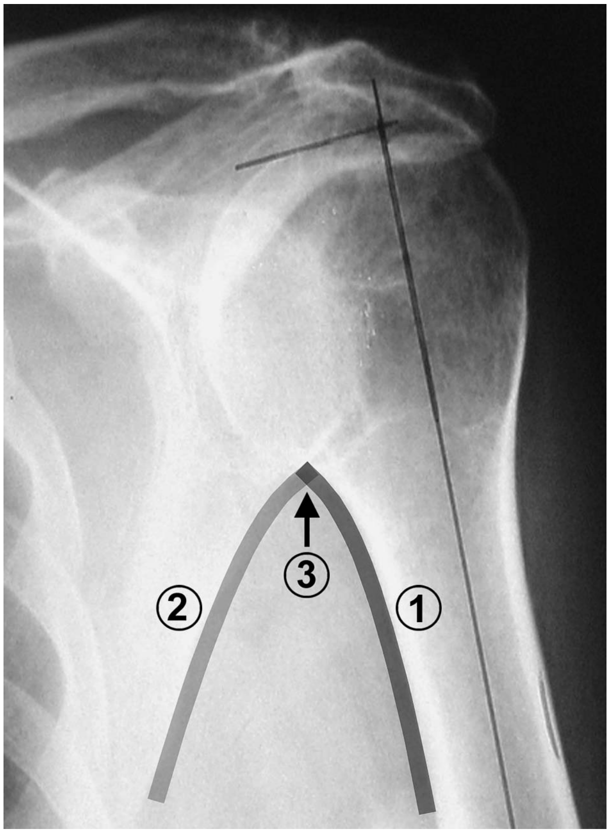


FIGURE 6. The "gothic arch" of a normal shoulder girdle: 1) Outline the medial border of the proximal humeral shaft ("medial calcar") to the base of the humeral articular surface; 2) Outline the lateral border of the scapula to the base of the glenoid articular surface; 3) Joining these lines creates a classic "vaulted" arch or "gothic arch" shape.

epicondyle to the top of the humeral head is calculated. On the injured scaled X-ray, the length from the medial epicondyle to the superior edge of the fracture (F) at the medial calcar is calculated. Once radiographic magnification (using the scale on each X-ray) is corrected, N minus F equals the fracture to top of head height (H). This can be marked on the prosthetic implant.

Step 2 (X-Ray): Greater Tuberosity Length (Fig. 8A and B)

Anatomic studies have documented that the top of the greater tuberosity of the humerus sits approximately 3–5 millimeters below the top of the humeral articular surface.[24,25] Using the scaled X-ray on the injured humerus, the greater tuberosity is identified. In most cases, the inferior and superior margins of this tuberosity fragment (even if comminuted) can be identified. The greater tuberosity length (G) is calculated, again accounting for radiographic magnification, and should be within 3–5 millimeters of the fracture to top of head height (H).

Step 3 (Intraoperative): Greater Tuberosity Measurement (Fig. 9A and B)

Once the greater tuberosity fragment is identified intraoperatively and controlled with sutures at the bone–tendon junction, the actual length of the tuberosity can be measured using a simple metal ruler. This actual measured length should be within 5 millimeters of the previous radiographic calculation of greater tuberosity length. This is the most important measurement of all and (if the radiographic measurements are not accurate when compared with this one as previously indicated) this measurement should supersede the others.

Step 4 (Intraoperative): Visualization of the Gothic Arch(Fig. 10A and B)

Once all measurements are calculated, and the appropriate mark is placed on the prosthetic implant, the implant is placed into the humeral shaft with the appropriately selected trial head. The lateral half of the gothic arch (medial calcar of the humerus up to the inferior margin of the anatomic neck) should be unbroken. If the arch is not "visualized," then either:

1. prosthetic height is incorrect (usually too high or "proud"—this is the most common technical error encountered);
2. medial calcar is fractured and has not been restored; or
3. head size is either too large or has not been rotated into the most "lateral" offset position—causing medial "overhang" of the inferior portion of the prosthetic head (this is the next most common technical error in prosthetic positioning after inappropriate height and excessive retroversion).

At this point either a trial X-ray or a fluoroscopic image can be used to confirm restoration of the gothic arch with the arm in neutral position. We recommend radiographic confirmation prior to definitive cementation if the operating surgeon is concerned or relatively inexperienced in shoulder fracture arthroplasty. As experience with these difficult cases grows, the gothic arch becomes more easily visible and inherently facile to recreate intraoperatively with the simple visual and measured landmarks described here. The 4 "steps" described above are "checks" against each other to ensure anatomic prosthetic positioning while attempting to reduce potential human error during radiographic measurements.

Anatomic Tuberosity Osteosynthesis

Two drill holes are placed in the proximal humeral shaft prior to final prosthetic cementation. Two #5 Ethibond sutures are placed in these holes in a horizontal mattress fashion to be used as "tension band" sutures for final

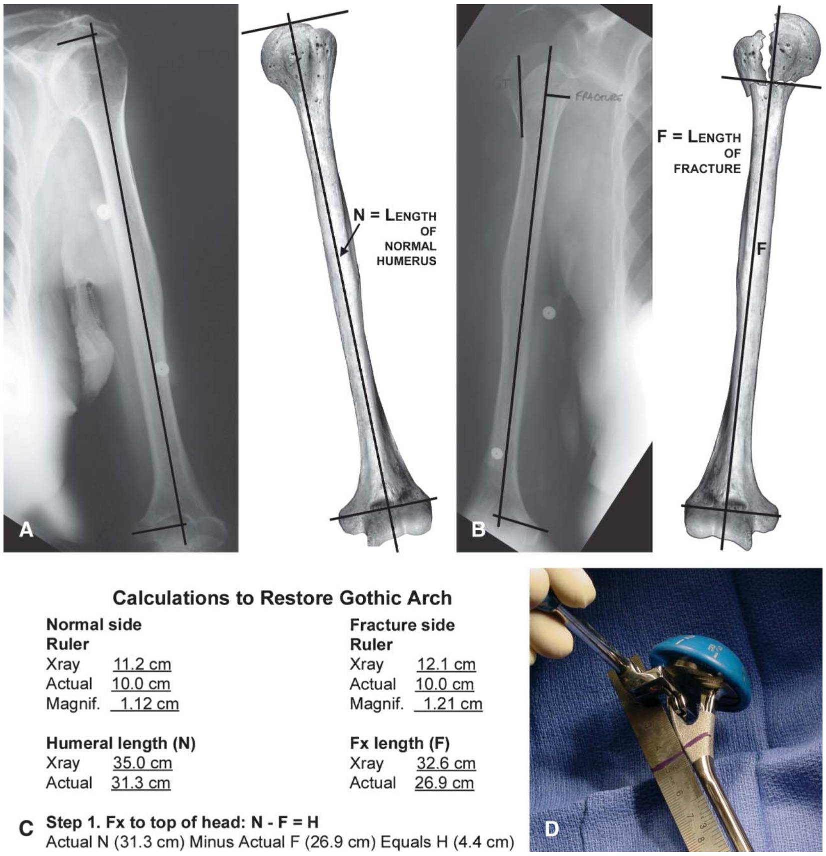


FIGURE 7. A, N = Entire length of normal humerus along perpendicular from medial epicondyle to top of humeral head. Use scaled ruler on X-ray to calculate radiographic magnification and obtain actual number. B, F = Length of injured humerus along perpendicular from medial epicondyle to fracture at superior edge of medial calcar. Use scaled ruler on X-ray to calculate radiographic magnification and obtain actual number. C, N minus F = H. H is the Fracture to Top of Head Height. D, Fracture to Top of Head Height is marked on actual prosthetic implant.

tuberosity osteosynthesis. The stem is cemented using a standard third-generation technique to the predetermined depth and rotation, in slight valgus. Three structural cancellous bone graft wedges that were previously obtained from the fractured humeral head are then placed as follows: 1) in the ‘‘window’’ of the fracture-specific prosthesis, 2) under the greater tuberosity at the ‘‘lateral’’ fin of the prosthesis, and 3) under the ‘‘medial’’ edge of the prosthetic head between the head and neck of the implant.

The details of the tuberosity osteosynthesis have been previously described but are reviewed here[6,7] (Fig. 11A). Two of the previously placed sutures in a horizontal fashion at the bone–tendon junction of the greater tuberosity

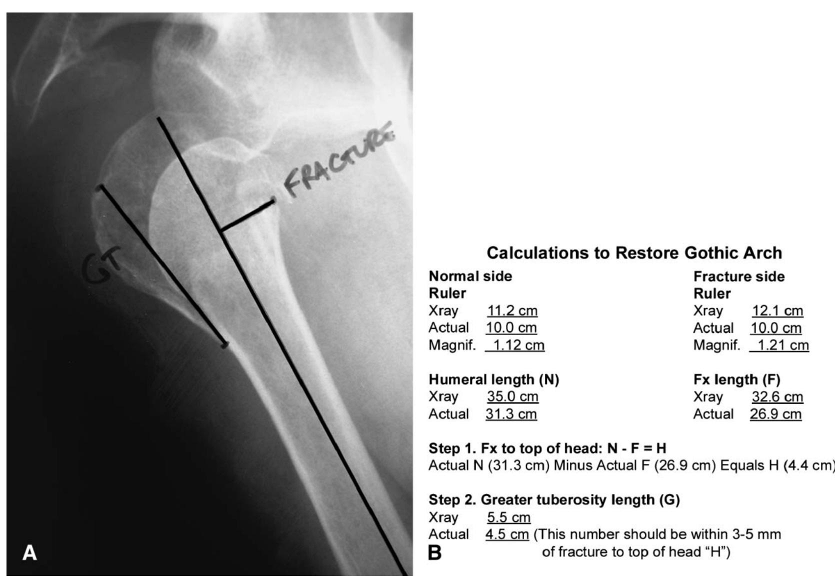
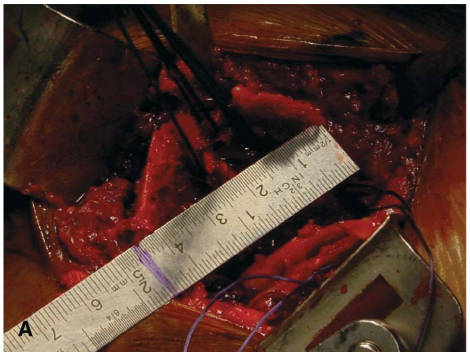


FIGURE 8. A, Greater Tuberosity Length (G) is measured and corrected for radiographic magnification using scale on X-ray. B, This number should be within 3–5 millimeters of the Fracture to Top of Head Height (H) that was marked on the prosthetic implant.



Calculations to Restore Gothic Arch

Normal side		Fracture side	
Ruler		Ruler	
Xray	11.2 cm	Xray	12.1 cm
Actual	10.0 cm	Actual	10.0 cm
Magnif.	1.12 cm	Magnif.	1.21 cm
Humeral length (N)		Fx length (F)	
Xray	35.0 cm	Xray	32.6 cm
Actual	31.3 cm	Actual	26.9 cm

Step 1. Fx to top of head: N - F = H
Actual N (31.3 cm) Minus Actual F (26.9 cm) Equals H (4.4 cm)

Step 2. Greater tuberosity length (G)
Xray 5.5 cm
Actual 4.5 cm (This number should be within 3-5 mm of fracture to top of head "H")

Step 3. Greater tuberosity measurement
Measurement 4.6 cm (This number should be within 5 mm of greater tuberosity length "G")

B

FIGURE 9. A, Actual measurement of greater tuberosity length using a metal ruler. B, This should be within 5 millimeters of the radiographic Greater Tuberosity Length (G) measure.

are now passed around the prosthetic neck and tied down over the structural bone graft (Fig. 11B). The remaining 2 previously placed horizontal Ethibond sutures are passed around the humeral neck and placed through the subscapularis tendon from posterior exiting anteriorly and tied down over the medial bone graft (Fig. 11C). The transosseous ''tension band'' sutures from the humeral shaft are used to create vertical tension on the osteosynthesis complex. One suture is passed anteriorly through the subscapularis tendon and supraspinatus tendons (anterosuperior cuff), while the other suture is passed posteriorly through the infraspinatus and supraspinatus tendons (posterosuperior cuff) (Fig. 11D).

The shoulder is placed through a full range of motion, to ensure no micromotion of the tuberosity fragments. Passive intraoperative range of motion should be at least 160° of elevation, 40° of external rotation, and 70° of internal rotation. The rotator interval or iatrogenic rotator cuff split is closed with the arm in 20–30° of external rotation, and the biceps is tenodesed within the intertubercular groove/rotator interval to soft tissue. Postoperative X-rays should demonstrate anatomic reconstruction of the proximal humerus (Fig. 12A and B).

POSTOPERATIVE CARE

Patients are placed into an Ultrasling orthosis (Donjoy Orthopedics, CA) for 6 weeks. Immediate passive motion is begun the day after surgery with motion limits dictated by the intraoperative evaluation following tuberosity osteosynthesis. Active motion is allowed at 7 weeks after surgery. Resistance exercises begin 10 weeks after surgery.

RESULTS

Between 2001 and 2003, 34 consecutive patients with displaced fractures of the proximal humerus underwent prosthetic hemiarthroplasty using the technique described here. There were 24 female and 10 male patients. Mean age at time of surgery was 72 years (range 43–93 years). Mean time from injury to surgery was 20 days (range 2–100 days). Indication for surgery was a displaced proximal humerus fracture or fracture-dislocation not amenable to head preservation. Mean postoperative follow-up was 18 months (range 12–24 months).

Two patients died by final follow-up, leaving 32 patients available for review. At final follow-up, mean American Shoulder and Elbow Surgeons (ASES) score

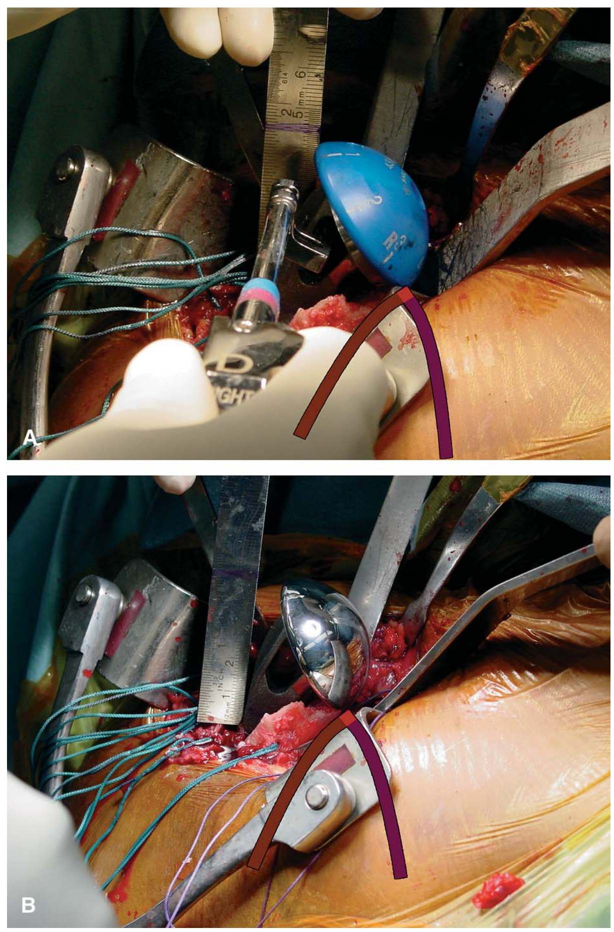


FIGURE 10. A, Gothic arch restoration with trial head on actual implant. Implant has been placed to predetermined mark and confirmed with ruler. B, Final gothic arch restoration.

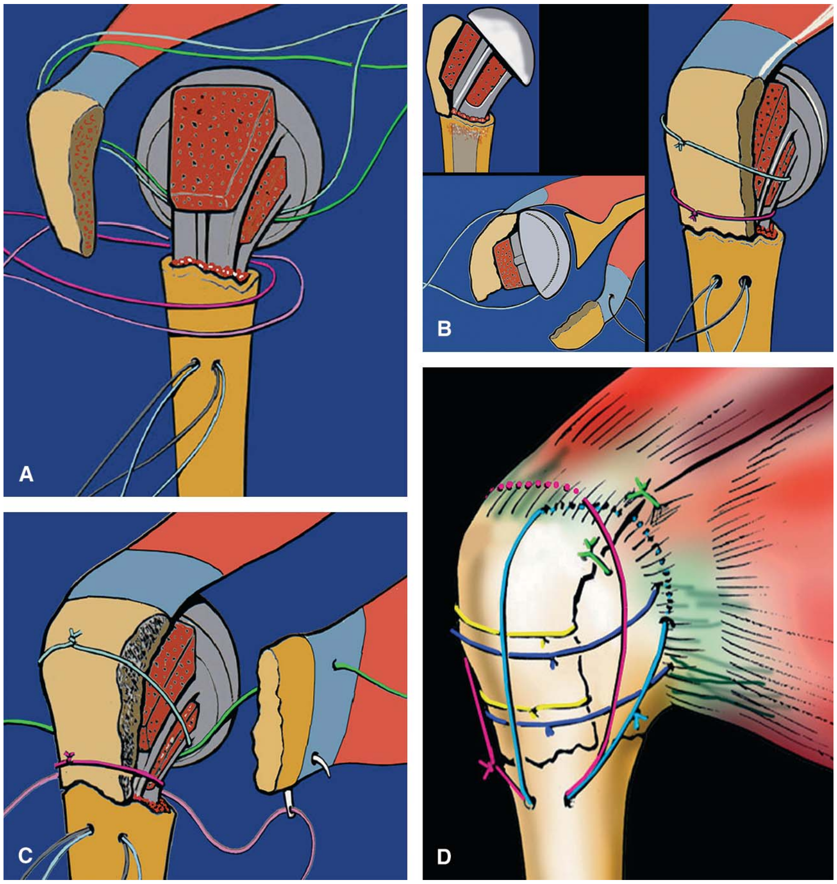


FIGURE 11. A, Six-suture configuration for anatomic tuberosity osteosynthesis. B, Greater tuberosity fixation over "lateral" bone graft. C, Lesser tuberosity fixation over "medial" bone graft. D, Final tuberosity osteosynthesis with "tension-band" sutures passed through anterosuperior and posterosuperior cuff.

was 52 (range 10–100). Mean active anterior elevation (AAE) was 117° (range 50–165°). Radiographically, 22 (81%) of greater tuberosities healed anatomically to the humeral shaft. Pain averaged 2.7 (0 = no pain; 10 = worst pain). Satisfaction averaged 7.2 (0 = unsatisfied; 10 = completely satisfied).

Fourteen patients (52%) demonstrated mean AAE under 120°. For these patients, mean age was 79 years. Mean time to surgery in this group was 36 days, and mean AAE was 96°. Five greater tuberosity fragments (36%) did not heal to the humeral shaft. Mean ASES score in this group was 42, with pain score of 3.6 and satisfaction score of 6.1.

Eighteen patients (48%) demonstrated mean AAE over 120°. For these patients, mean age was 65 years. Mean time to surgery in this group was 6 days, and mean AAE was 140°. Eighteen of 18 (100%) of greater tuberosity fragments healed to the humeral shaft in an anatomic fashion. Mean ASES score in this group was 66, with pain score of 1.7 and satisfaction of 8.3 ($P < 0.03$ for all parameters) (Table 1).

COMPLICATIONS

There were no infections or reoperations in this series. No cases of prosthetic instability or loosening occurred. The 2 deaths lost to follow-up were not in the near postoperative period and were not related to the surgery.

DISCUSSION AND FUTURE CONSIDERATIONS

Our experience indicates that precise positioning of the prosthetic hemiarthroplasty in 4-part fractures of the proximal humerus, with anatomic reconstruction and osteosynthesis of the critically important tuberosity fragments, is the key to improving clinical results in the

TABLE 1. *Results of shoulder replacement for fractures for two groups divided based on mean active anterior elevation either above or below 120°*

No.	Age	Mean ASES Score	AAE	GT healed?	Mean time from injury to surg	Pain (0–10 scale)
14	79 yrs	42	96°	9 (64%)	36 days	3.6
18	65 yrs	66	140°	18 (100%)	6 days	1.7

$P < 0.03$ for all parameters.

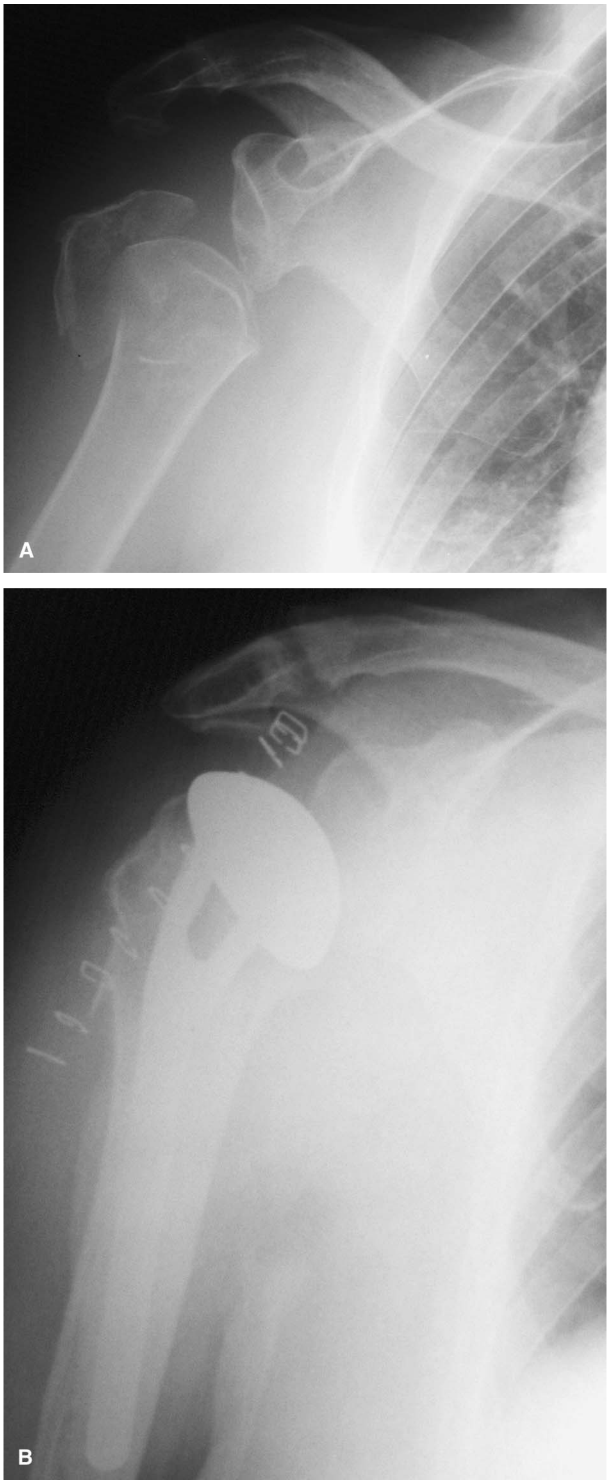


FIGURE 12. A, Four-part proximal humerus fracture with broken gothic arch. B, Restoration of the gothic arch and anatomic tuberosity osteosynthesis.

treatment of these complex injuries. Hence, a shoulder prosthesis for fracture should be considered an ''augmented'' osteosynthesis, with precise prosthetic implantation supplementing anatomic tuberosity reconstruction. Successful tuberosity osteosynthesis to the humeral shaft appears to depend both on accurate prosthetic implantation and on fixation adequate to withstand early passive motion.

The short-term results reported here also seem to indicate that functional outcome in the treatment of these injuries is dependent both on age and time from injury to surgery, but pain relief after shoulder fracture arthroplasty appears reliable and predictable in nearly all patients. Furthermore, the outcomes reported here seem to support a shorter conservative trial (less than 3 weeks) if arthroplasty is being considered for a displaced proximal humerus fracture. These findings may also guide the all-important preoperative discussions with these patients regarding the postoperative potential both for pain relief (very high) and for functional overhead motion (dependent on age and time to surgery).

We believe that the use of the medial calcar of the humerus with restoration of the ''gothic arch'' provides surgeons an objective and reproducible technique for fracture arthroplasty. With contralateral templating of the normal uninjured humerus and intraoperative restoration of the measured humeral height and tuberosity length, an anatomic reconstruction may indeed be possible in nearly every case. To our knowledge, the technique used here demonstrates an overall incidence of tuberosity healing to the humeral shaft (81%) that exceeds any technique previously reported in the recent peer-reviewed literature. Further investigations are ongoing regarding the use of specific fracture implants as well as biologic substrates in an attempt to further improve the rate of tuberosity healing in the older patient population after this operation.

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