Acta Orthop. Belg., 2015, **81**, 501-510

ORIGINAL STUDY

Operative management of humeral nonunions. Factors that influence the outcome

Antonios KOUTALOS, Sokratis VARITIMIDIS, Zoe DAILIANA, Konstantinos BARGIOTAS, Alexandros KOUTSOGIANNIS†, Konstantinos N. MALIZOS

From the Department of Orthopaedic Surgery and Musculoskeletal Trauma, University Hospital of Thessalia, Greece

The purpose of this study is to present the outcome of surgically treated humeral nonunions and find factors that affect the outcome. Forty-two patients with humeral nonunions (30 shaft, 7 proximal and 5 distal) were reviewed in a prospective manner. Treatment was based on a specific algorithm. Demographics, time to union, range of motion, functional outcome and complications were recorded and analysed. Results: Mean follow-up was 78 months and mean time to union was 4.3 months. Infection was associated with delayed union of the pseudarthrosis, while range of motion was negatively affected by the location (proximal) and the AO type of the initial fracture. Complication rate was 17%. *Conclusion:* The surgical management of humeral nonunions yields a favourable outcome with reduced rate of complications. Infection prolonged healing time, while proximal location of the nonunion and the type B or C fracture according to AO/OTA classification adversely affected range of motion.

Keywords : humeral nonunion ; plate fixation ; bone graft; infection; atrophic nonunion.

INTRODUCTION

Nonunion of humeral fractures after conservative or surgical treatment represents a disabling condition for the patient and a challenge for the surgeon. The rate of nonunion ranges between 2% and 20% after conservative treatment and between 8% and 12% after operative treatment (*6,28*). Risk factors associated with nonunion include age, history of smoking or alcoholism, open fracture, mechanism of injury, initial treatment, infection, fracture pattern (*13,26*).

Treatment of nonunion ranges from low intensity pulsed ultrasound and administration of parathyroid hormone (PTH) in case reports (*22,23*) to surgical treatment with plate fixation (single or double, locking or not) (*10,15,27,28*), intramedullary nails and external fixation (*25*). Patients with serious

■ Antonios Koutalos, MD.
■ Sokratis Varitimidis, MD, PhD.
■ Zoe Dailiana, MD, PhD.
■ Konstantinos Bargiotas, MD, PhD.
■ Alexandros Koutsogiannis, MD.
■ Konstantinos N. Malizos, MD, PhD.
Department of Orthopaedic Surgery and Musculoskeletal Trauma, Faculty of Medicine, University of Thessalia, Greece.
Correspondence : Sokratis E Varitimidis, MD, PhD, Department of Orthopaedic Surgery and Musculoskeletal Trauma, Faculty of Medicine, University of Thessalia, Biopolis,41500, Larissa, Greece.
E-mail : svaritimidis@ortho-uth.org

No benefits or funds were received in support of this study. The authors report no conflict of interests.

medical comorbidities might be better if left with no intervention. For proximal nonunions unconstrained (hemiarthroplasty or total shoulder) arthroplasty, reverse shoulder arthroplasty and 90 degrees angle blade plate has been used (*1,7,11,18*). For distal nonunions, plate fixation and total elbow arthroplasty are viable options (*2,30*). For nonunions with bone loss, vascularized bone grafts, cortico-cancelous bone grafts and external fixation is preferred (*3,25*). External fixation is often used in cases complicated by infection (*26-29*). Iliac crest autografts or allografts play a major role in treating nonunions (especially atrophic) due to osteo-conductive and osteoinductive properties (*15*).

Table I. — Patients' demographics

	n	Percentage (%)
Sex		
male	11	26
female	31	74
Cause of injury		
Low energy	24	57
High energy	18	43
Shaft fractures (n = 30)		
Type A (AO/OTA)	20	47
Type B	7	17
Type C	3	7
Proximal fractures (n = 7)		
Type A (AO/OTA)	4	10
Type B	1	2
Type C	2	5
Distal fractures (n = 5)		
Type A (AO/OTA)	1	2
Type B	2	5
Type C	2	5
Complicated		
Closed fractures	37	88
Open fractures	5	12
Initial treatment		
IM nail	15	36
Plate	6	14
Ex fix	4	10
K-ws	3	7
Nonoperative	14	33
Infection		
Yes	13	31
No	29	69
Type of non union		
Hypertrophic	7	17
Atrophic	24	57
Septic	11	26

The majority of humeral nonunions are treated with plate osteosynthesis. The purpose of this study is to evaluate the factors that influence the outcome after operative treatment of humeral nonunions with different methods or techniques.

PATIENTS AND METHODS

From January 1990 to May 2010, fifty skeletally mature patients (37 women and 13 men) were treated for nonunion of humeral fractures. Electronic records were retrospectively reviewed and analyzed. Patient consent was obtained from all patients. The patients met the inclusion criteria: 1. Established nonunion of humeral fractures, defined as no healing after 24 weeks, no progression of callus formation on three consecutive monthly radiographic examinations 2. A minimum of 24 months follow-up after surgery for non-union. Seven patients were excluded because of inadequate follow-up, one deceased (from reasons unrelated to treatment) leaving forty-two patients for analysis. Causes of the initial injury included traffic accident, fall from height or gunshot in 18 patients (high energy injuries) while fall from standing height or direct blow was the cause in 24 patients (low energy injury). The fracture types according to AO/OTA classification for shaft fractures were A (n = 20), B (n = 7) and C (n = 3). There were 30 shaft fractures, seven distal third fractures (four A, one B and two C fracture type according to AO/OTA classification) and five proximal third fractures (one A, two B and two C type). Five were open and 37 were closed. Initial treatment consisted of IM nailing (n = 15), plate fixation (n = 6), external fixation (n = 4), Kirschner wires (n = 3) whereas fourteen patients were treated conservatively. In the patients that were treated surgically initially, the average number of prior surgeries was 2 (range 1-8). Infection of soft tissues was diagnosed in 2 patients and septic nonunion (including 9 "surprise" septic nonunions) was diagnosed in 11 patients (Table I, Fig. 1). There was one patient with radial nerve palsy that was managed with tendon transfers and one patient with axillary nerve laceration that did not recover after nerve repair.

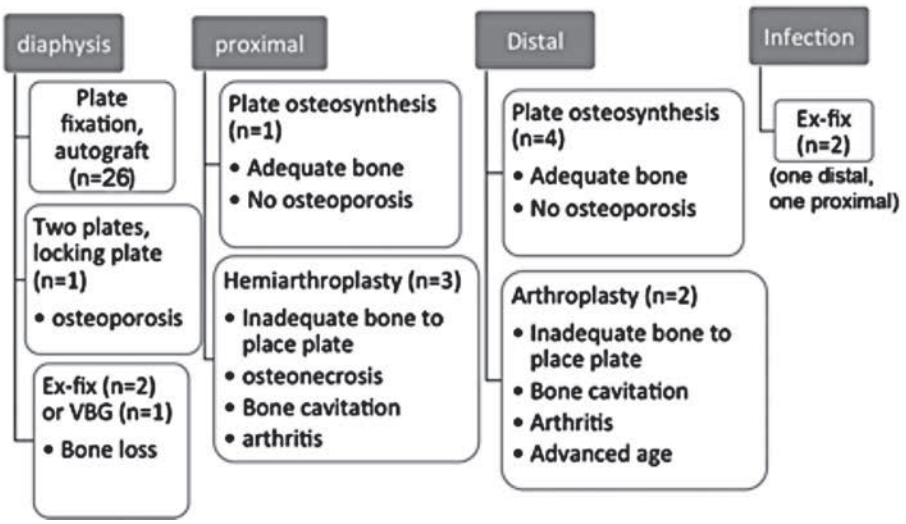

Fig. 1. — Treatment algorithm.

Fig. 2. — Preoperative x-ray of a sixty-five year-old female who sustained a spiral fracture of right humeral diaphysis depicting nonunion after 6 months of concervative treatment.

Fig. 3. — Postoperative view depicting stable osteosynthesis with an inter-fragmentary lag screw and broad plate.

Fig. 4. — X-ray of three months follow-up. The patient had no pain or tenderness at the previous nonunion site. Clinical healing was diagnosed.

Nonunion was diagnosed if there was no evidence of healing after 24 weeks, no progression of callus formation on three consecutive monthly radiographic examinations (Figs. 2-10) (10). The mean time from fracture to surgery was 9.2 ± 6.4 months (range 3-36 months). The nonunion was classified as atrophic (n = 24), hypertrophic (n = 7) or septic (n = 11) according to criteria reported by Megas *et al* (Table I) (20).

Treatment

Our algorithm for the management of the humeral nonunions is shown in Figure 1. The majority of the fractures were managed with open reduction and internal fixation. Shoulder hemiarthroplasty (n = 3), total elbow arthroplasty (n = 2), external fixation (n = 4) and vascularized bone graft (n = 1) was also used when

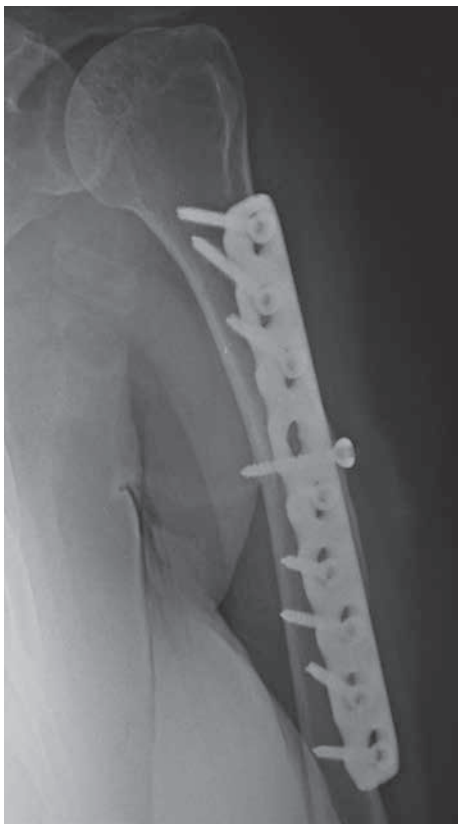

Fig. 5. — X-ray of the same patient after four years with excellent clinical outcome.

Fig. 6. — Preoparative x-ray of a forty-one year-old female who sustained a spiral fracture of the right humeral diaphysis. Unsuccessful treatment with intramedulary nail led to atrophic union after 6 months.

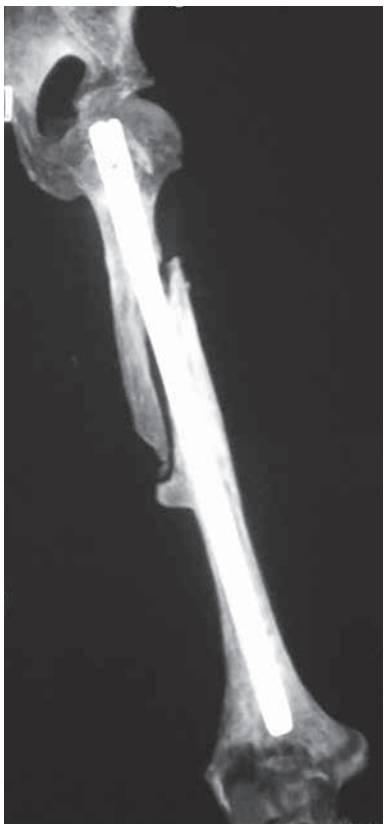

Fig. 7. — CT reconstruction of the same patient depicting nonunion of the fracture.

indicated (Fig. 1). The posterior approach was used to treat the distal mid-shaft and distal (supracondylar) nonunions with the addition of olecranon osteotomy if required. For distal humerus nonunions, joint contraction release and ulnar nerve anterior transposition was utilized. The deltopectoral approach was used for proximal nonunions. For the majority of diaphyseal nonunions, the anterolateral approach was chosen. After exposure of the nonunion site, previous implants were removed. The nonunion was debrided, both ends were decorticated and the medullary canal was opened. Sclerotic bone was removed until healthy live bone was reached (paprika sign). The fracture was reduced and fixed with broad 4.5 plates and screws engaging at least eight cortices. Iliac crest autograft was used in all patients (Fig. 3-4, 8-10). In 10 patients with atrophic nonunion that persisted for long time a BMP (Bone Morphogenic Protein) was added to bone autograft. In all approaches the radial nerve was dissected and protected.

The humerus was immobilized with a sling for one to two weeks depending on the kind of treatment that was used. Range of motion exercises were allowed afterwards. Patients were followed-up monthly until fracture healing (Fig. 5).

Radiographic, clinical and functional analysis

Smoking, obesity and history of osteoporosis or alcoholism were recorded. Osseous healing was defined as the presence of at least three or four healed cortices with bridging callus formation and crossing trabeculae on anteroposterior and lateral radiographs. Clinical healing was defined as no pain or tenderness at the previous nonunion site (primary outcome) *(15)*.

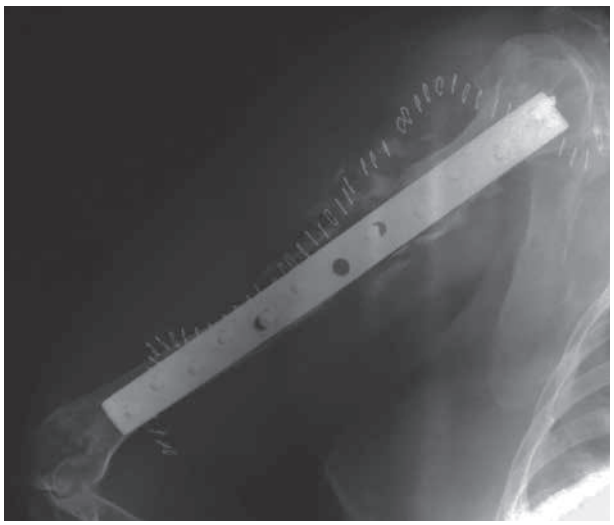

Fig. 8. — Postoperative view depicting stable osteosynthesis with a broad plate. Autograft and BMP-7 was added to enhance the union.

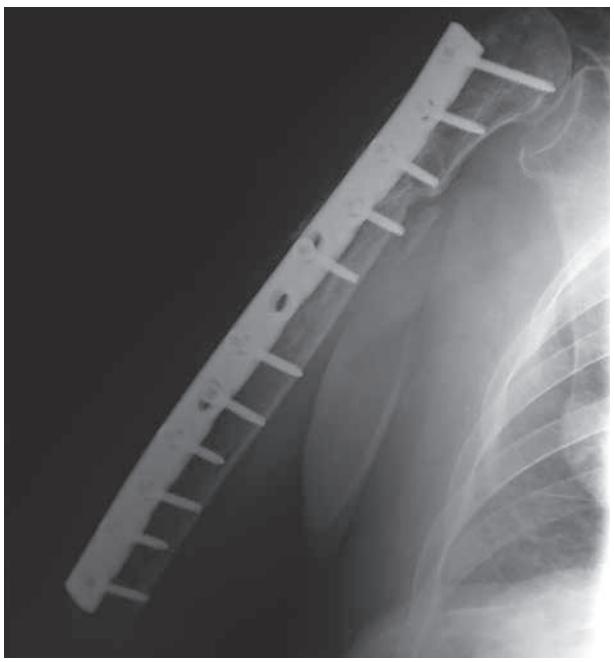

Fig. 9. — Anteroposterior x-ray depicting healed medial cortex after 4.5 months follow up.

Range of motion (ROM) of the shoulder (forward flexion, abduction, external and internal rotation at the side of the body) and ROM at the elbow joint (flexion, extension, supination, pronation) was recorded. The American Shoulder and Elbow Surgeons Standardized Shoulder Assessment Form (ASES score) for shoulder

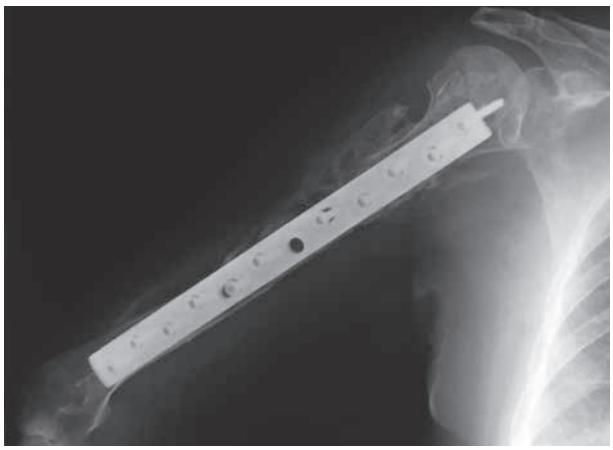

Fig. 10. — Lateral X-ray depicting anterior and posterior healed cortices at 4.5 months follow-up. The presence of excess bone formation is probably related to BMP use. The patient had no pain or tenderness at the nonunion site.

and the Mayo Clinic performance index were used. Also the Disabilities of the Arm, Shoulder and Hand (DASH) and the 12-Item Short Form Health Survey (SF-12) instruments were used for measuring patient based outcomes (*31*).

Complications were also recorded and grouped as major, intermediate or minor. Major complications consisted of infections or those requiring intervention. Intermediate defined as symptoms that persisted more than six weeks but disappeared eventually and minor as symptoms that persisted for less than six weeks (*15*).

The results were presented with the use of descriptive statistics. Furthermore, the effect of variables on several outcomes (complications, functional scores, ROM, strength) were examined with the use of chi-square, t-test for independent samples or Mann-Whitney tests where normality did not hold. The variables were then used in a logistic regression model under Firth's correction or in general linear models.

RESULTS

The mean time of follow-up was 78 (range 24-144) months. All nonunions healed except two diaphyseal pseudarthrosis, which were managed with repeat osteosynthesis with autograft and eventually united. The mean time to union was 4.3 ± 2.3 months overall. For shaft nonunions, the mean time to healing was 3.98 ± 1.27, whereas for distal pseudarthrosis the mean time was 3.80 ± 1.44

months. Three of the five proximal nonunions were treated with hemiarthoplasty and the remaining two were treated with open reduction and internal fixation (one patient) and with application of external fixation (one patient). The time to union was 4.5 and 15 months respectively in these two patients.

General linear model did not reveal any variable to be associated with healing time. The use of BMPs had no effect on healing time in the patients where it was used [healing time with BMPs was 5.1 ± 3.6 months while healing time without BMPs was 3.9 ± 1.1 (t-test, p = 0.17)].

In a different model, a cutoff at 4.5 months was chosen. Twenty three patients had a healed nonunion while 14 had not at 4.5 months (two patients had total elbow arthroplasty and three had shoulder hemiarthroplasty). These patients healed until the 7th month with the exception of one patient that healed at 15 months. The cutoff of 4.5 months was chosen based on literature data (*4,15,32*). Infection was the only risk factor in this model that was associated with delayed healing of the nonunion (p = 0.038).

Range of motion data are displayed in table II. In the subgroup of proximal nonunions, the mean abduction / externar rotation was 90 / 35 degrees for those patients treated with ORIF and 35 / 23 degrees for those treated with hemiarthroplasty. In the subgroup of distal nonunions the mean flexion – extension arc was 95 degrees for those patients treated with ORIF and 110 degrees for those treated with total elbow arthroplasty. General linear model analysis revealed that the location and the AO/OTA classification type had significant effect on postoperative shoulder abduction (Table III). Proximal nonunions that were

Table II. — Range of motion

		Mean (degrees)	SD
Shoulder abduction		101	33
Shoulder forward flexion		100	39
Shoulder external rotation		48	18
Shoulder internal rotation		51	18
Elbow flexion		128	6
Elbow extension		-3	9
Elbow supination		69	6
Elbow pronation		71	2
Strength	Shoulder	74	34
	Elbow	87	24

Table III. — Table depicting the statistically significant results after comparison of subgroups

Outcome measurement[a]	Comparisons of subgroups[b]	Variable estimate	Std. Error	Sig. (p value)	95% Confidence Interval
Shoulder abduction postoperatively	Diaphysis vs proximal (difference in degrees)	50.2	11.0	0.001	26-74
	AO type A vs AO type B (difference in degrees)	43.8	10.5	0.003	15-73
	AO type A vs AO type C (difference in degrees)	30.2	11.3	0.057[c]	-0.8-61
Shoulder flexion postoperatively	Diaphysis vs proximal (difference in degrees)	53.3	16.6	0.005	19-88
Shoulder external rotation postoperatively	Diaphysis vs proximal (difference in degrees)	26	7.5	0.003	10.2-41.8
Elbow flexion strength (% to contra-lateral) postoperatively	Closed vs open (difference)	46	10.9	0.001	23-70

[a] The outcomes used in this study was: healing time, shoulder abduction postoperatively, shoulder flexion postoperatively, shoulder external rotation postoperatively, elbow extension postoperatively, elbow flexion postoperatively, ROM elbow difference (flexion-extension) postoperatively, strength shoulder postoperatively %, strength postoperatively elbow [flexion] %.

[b] The variables (subgroups) that was tested in this study was: gender, open or not fracture, infection, smoking, prior surgeries, age, causes (high energy or low energy), AO type, location (proximal, distal, diaphysis), initial management of the fracture (conservative or surgery), time to surgery, if the case was referred or not, type of nonunion (hypertrophic, atrophic, septic), obesity, osteoporosis, alcoholism.

[c] In this comparison there was a trend for significance (p = 0.057).

treated with total shoulder arthroplasty or plate fixation had 50.2 less degrees of abduction ($p < 0.001$) (CI = 26, 74). Type B and C initial fractures had 43.8 ($p = 0.003$) (CI = 15, 73) and 30.2 ($p = 0.057$) (CI = -0.8, 63) less degrees of abduction than type A fractures respectively. Location of the nonunion had also a significant effect on shoulder flexion and shoulder external rotation. So, proximal nonunions had 53.3 less degrees of shoulder forward flexion postoperatively ($p < 0.005$) (CI = 19, 88) and 26 less degrees of postoperative external rotation ($p = 0.003$) (CI = 10.2, 41.8). In addition open fractures had 46% absolute reduction in flexion strength of the elbow ($p = 0.001$) (CI = 23, 70) (Table III).

Function was measured with instruments specific to the shoulder, elbow or the whole upper limb (DASH score). Quality of life measurements were also recorded. The results are shown in the table IV. Analysis did not reveal any variable that had a statistically significant effect on these measurements.

The complication rate was 17% in this series. There were three transient radial nerve palsies (7%) that resolved with observation alone (intermediate complication). In addition four major complications occurred. Two pseudarthroses (both of them diaphyseal) failed to unite and were successfully managed with revision of osteosynthesis and autograft. Another two nonunions (one distal and one diaphyseal) were complicated with infection needing serial surgical debridements for eradication. None of the tested variables were found to be correlated with complications. These variables included gender, open or not fracture, infection, smoking, prior surgeries, age, causes (high energy or low energy), AO type, location (proximal, distal, diaphysis), initial management of the fracture (conservative or surgery), time to surgery, if the case was referred or not, type of nonunion (hypertrophic, atrophic, septic), obesity, osteoporosis, alcoholism (Table V).

Table IV. — Functional outcome

		Mean	SD
ASES score		79	26
Mayo elbow score[a]		97	6
DASH score		19	24
SF-12 score	PCS[b]	48	10
	MCS[c]	56	8

[a] 37 patients had excellent Mayo elbow score (88%) and five patients had good Mayo elbow score (11%).
[b] physical component summary.
[c] mental component summary.

DISCUSSION

The gold standard for the treatment of humeral diaphysis nonunion is plate osteosynthesis combined with autograft. Open reduction and internal fixation (ORIF) results in union rates above 90% (*26*). For juxstrarticular nonunions a joint replacement may be selected in cases of osteoporosis, inadequate bone to place a plate or in cases of arthritic changes in the neighboring joint. Our algorithm is shown in

Table V. — Logistic regression model under Firth's correction for investigating factors associated with complications after surgery for humeral nonunion. None of them is statistically significant

Variable	Odds Ratio	Std. Err.	P value	95% Confidence Interval
Open or not	12.74	29.5	0.272	0.135-1198
Location (proximal, distal, diaphysis)	0.24	0.46	0.464	0.005-11
Infection	0.81	2.52	0.947	0.002-349
Causes (high or low energy)	0.53	0.95	0.727	0.016-17
Type of non union (hypertrophic, atrophic, septic)	0.75	1.14	0.852	0.039-14
Prior surgeries	0.88	0.47	0.821	0.31-2.53
Initial management of fracture (conservative or surgical)	1.26	1.86	0.873	0.07-22.5
Time to surgery	1.01	0.08	0.825	0.86-1.2
Smoking	0.38	0.60	0.546	0.017-8.6

Figure 1 (*26*). The time to union depends on many variables related to the surgeon and the fixation method (initial treatment, number of surgeries, autograft), the host (gender, age, smoking, osteoporosis, obesity, alcoholism) and the nonunion itself (location, type of nonunion, infection). Some of these factors have been demonstrated to affect union and the time to union in humeral fractures. Court-Brown at al found that age, displacement and metaphyseal comminution of a proximal fracture might lead to nonunion (*5*). Delayed union is observed in patients with obesity or alcoholism (*16*). In cases of nonunion the use of autograft has been shown to positively affect the union of pseudarthrosis, while smoking has a negative influence (*1,17*). In this series autograft could not be evaluated as an independent factor, as it was used in all patients. Our statistical analysis revealed infection as a factor for delayed union of the pseudarthrosis.

Regarding ROM of the shoulder, ROM of the elbow and grip strength, the results rely on many variables. Location is one of them. ROM after surgery for proximal nonunions varies according to treatment. Yamane achieved 122 degrees elevation and 35 degrees external rotation in patients treated with locking nail (*33*), while Duralde reports 86 degrees postoperative elevation and 37 degrees external rotation with plate osteosynthesis (*8*). In contrast Galatz achieved 143 degrees of elevation in patients treated with ORIF (*11*). Total shoulder arthroplasty or hemiarthoplasty is thought to have inferior results in ROM compared to other methods (*12*) but is more predictive in pain relief. This is why reverse shoulder arthroplasty has been recently selected for the treatment of proximal humeral nonunions (*18*). In this series the ROM was 90/35 (abduction/ external rotation) degrees for plate osteosynthesis and 35/23 (abduction/ external rotation) degrees for hemiarthroplasty. In distal nonunions the ROM is comparable with either total elbow arthroplasty or plate osteosynthesis. Arc of flexion is reported to be 110 degrees in total elbow arthroplasty (TEA) (*9,21*), between 94 and 97 degrees in plate osteosynthesis (*14,19*) and 109 in Ilizarov external fixation (*29*). The mean ROM in the present study was 95 degrees for ORIF and 110 degrees for TEA.

General linear models revealed that diaphyseal nonunions had better ROM (abduction, forward flexion and external rotation) when compared with proximal location of the pseudarthrosis. Proximal nonunions may be complicated with the formation of contractions resulting in reduced ROM. McKee has shown that contraction release during surgery increases the ROM (*19*). In addition abduction was better in cases of simpler initial fracture (A compared to B and C). Strength of the elbow was negatively associated with the presence of open fracture. This may be explained from the fact that open fractures are accompanied with soft tissue loss (from the trauma itself or from the surgical debridement). However, the differences in ROM did not translate into functional discrepancies.

Evaluation of function in patients with humeral nonunions is rarely reported and general quality of life questionnaires are even more scarcely employed. Dompsure *et al* found a constant score of 77 and Mayo score of 97 in diaphyseal nonunions treated with ORIF (*4*). In distal nonunions Safoury *et al* reports that the Mayo score was 79 (*29*). Otsuka measured SF-12 and Constant score in patients treated with humeral nonunions and reached the conclusion that comorbidities had a large effect on SF-12 but no effect on Constant score (*24*). In this study the SF-12 score was also not associated with any variable related to nonunion. DASH score was not correlated with any tested variable. Strict adherence to indications and meticulous technique provided the best possible result to the patients, achieving a good functional outcome despite the difficultly of the management.

Limitations of this study are its retrospective nature and the lack of a control group. The application of multiple methods may be a confounding factor but in general most nonunions were managed with compression plate osteosynthesis and autograft. Newer techniques like reverse shoulder arthroplasty were not used (*18*). The inclusion of distal and proximal cases added another confounding factor, but we believe that these acted more like a control group to make useful comparisons. Finally, the small number of patients did not allow us to show some differences as statistical significant.

In conclusion, it can be postulated that the surgical management of humeral nonunions results in excellent union rates (95%), satisfactory functional outcome, with reduced complication rate (16%) and revision ORIF (5%). In the present series infection was associated with delayed healing. Proximal nonunions and the type B or C fracture according to AO/OTA classification negatively influenced the ROM. Open fractures had less flexion strength of the elbow.

REFERENCES

1. **Allende C, Allende BT.** The use of a new locking 90 degree blade plate in the treatment of atrophic proximal humerus nonunions. *Int Orthop* 2009 ; 33 : 1649-1654.
2. **Baksi DP, Pal AK, Baksi D.** Prosthetic replacement of elbow for intercondylar fractures (recent or ununited) of humerus in the elderly. *Int Orthop* 2011 ; 35 : 1171-1177.
3. **Beredjiklian PK, Hotchkiss RN, Athanasian EA *et al.*** Recalcitrant nonunion of the distal humerus: treatment with free vascularized bone grafting. *Clin Orthop Relat Res* 2005 ; 435 : 134-139.
4. **Bernard de Dompsure R, Peter R, Hoffmeyer P.** Uninfected nonunion of the humeral diaphyses: review of 21 patients treated with shingling, compression plate, and autologous bone graft. *Orthop Traumatol Surg Res* 2010 ; 96 : 139-146.
5. **Court-Brown CM, McQueen MM.** Nonunions of the proximal humerus: their prevalence and functional outcome. *J Trauma* 2008 ; 64 : 1517-1521.
6. **Denard A Jr, Richards JE, Obremskey WT *et al.*** Outcome of nonoperative vs operative treatment of humeral shaft fractures: a retrospective study of 213 patients. *Orthopedics* 2010 ; 33 (8).
7. **Duquin TR, Jacobson JA, Sanchez-Sotelo J *et al.*** Unconstrained shoulder arthroplasty for treatment of proximal humeral nonunions. *J Bone Joint Surg Am* 2012 ; 94 : 1610-1617.
8. **Duralde X A, Flatow E L, Pollock R G *et al.*** Operative treatment of nonunions of the surgical neck of the humerus. *J Shoulder Elbow Surg* 1996 ; 5 : 169-180.
9. **Espiga X, Antuña SA, Ferreres A.** Linked total elbow arthroplasty as treatment of distal humerus nonunions in patients older than 70 years. *Acta Orthop Belg* 2011 ; 77 : 304-310.
10. **Foster RJ, Dixon GL Jr, Bach AW *et al.*** Internal fixation of fractures and non-unions of the humeral shaft. Indications and results in a multi-center study. *J Bone Joint Surg Am* 1985 ; 67 : 857-864.
11. **Galatz LM, Williams GR Jr, Fenlin JM Jr *et al.*** Outcome of open reduction and internal fixation of surgical neck nonunions of the humerus. *J Orthop Trauma* 2004 ; 18 : 63-67.
12. **Healy WL, Jupiter JB, Kristiansen TK *et al.*** Nonunion of the proximal humerus. A review of 25 cases. *J Orthop Trauma* 1990 ; 4 : 424-431.
13. **Healy WL, White GM, Mick CA *et al.*** Nonunion of the humeral shaft. *Clin Orthop Relat Res* 1987 ; 219 : 206-123.
14. **Helfet DL, Kloen P, Anand N, Rosen HS.** Open reduction and internal fixation of delayed unions and nonunions of fractures of the distal part of the humerus. *J Bone Joint Surg Am* 2003 ; 85 : 33-40.
15. **Hierholzer C, Sama D, Toro JB *et al.*** Plate fixation of ununited humeral shaft fractures: effect of type of bone graft on healing. *J Bone Joint Surg Am* 2006 ; 88 : 1442-1447.
16. **Jupiter JB, von Deck M.** Ununited humeral diaphyses. *J Shoulder Elbow Surg* 1998 ; 7: 644-653.
17. **Lammens J, Bauduin G, Driesen R *et al.*** Treatment of nonunion of the humerus using the Ilizarov external fixator. *Clin Orthop Relat Res* 1998 ; 353 : 223-230.
18. **Martinez AA, Bejarano C, Carbonel I *et al.*** The treatment of proximal humerus nonunions in older patients with reverse shoulder arthroplasty. *Injury* 2012 ; 43 Suppl 2 : S3-6.
19. **McKee M, Jupiter J, Toh CL *et al.*** Reconstruction after malunion and nonunion of intra-articular fractures of the distal humerus. Methods and results in 13 adults. *J Bone Joint Surg Br* 1994 ; 76 : 614-621.
20. **Megas P.** Classification of non-union. *Injury* 2005 ; 36 Suppl 4 : S30-7.
21. **Morrey BF, Adams RA.** Semiconstrained elbow replacement for distal humeral nonunion. *J Bone Joint Surg Br* 1995 ; 77 : 67-72.
22. **Nolte PA, van der Krans A, Patka P *et al.*** Low-intensity pulsed ultrasound in the treatment of nonunions. *J Trauma* 2001 ; 51 : 693-702.
23. **Oteo-Alvaro A, Moreno E.** Atrophic humeral shaft nonunion treated with teriparatide (rh PTH 1-34): a case report. *J Shoulder Elbow Surg* 2010 ; 19 : e22-28.
24. **Otsuka NY, McKee MD, Liew A *et al.*** The effect of comorbidity and duration of nonunion on outcome after surgical treatment for nonunion of the humerus. *J Shoulder Elbow Surg* 1998 ; 7 : 127-133.
25. **Patel VR, Menon DK, Pool RD, Simonis RB.** Nonunion of the humerus after failure of surgical treatment. Management using the Ilizarov circular fixator. *J Bone Joint Surg Br* 2000 ; 82 : 977-983.
26. **Pugh DM, McKee MD.** Advances in the management of humeral nonunion. *J Am Acad Orthop Surg* 2003 ; 11 : 48-59.
27. **Ring D, Kloen P, Kadzielski J *et al.*** Locking compression plates for osteoporotic nonunions of the diaphyseal humerus. *Clin Orthop Relat Res* 2004 ; 425 : 50-54.
28. **Rubel IF, Kloen P, Campbell D *et al.*** Open reduction and internal fixation of humeral nonunions: a biomechanical and clinical study. *J Bone Joint Surg Am* 2002 ; 84 : 1315-1322.
29. **Safoury YA, Atteya MR.** Treatment of post-infection nonunion of the supracondylar humerus with Ilizarov

external fixator. *J Shoulder Elbow Surg* 2011 ; 20 : 873-879.

30. **Sanders RA, Sackett JR.** Open reduction and internal fixation of delayed union and nonunion of the distal humerus. *J Orthop Trauma* 1990 ; 4 : 254-259.
31. **Smith MV, Calfee RP, Baumgarten KM *et al.*** Upper extremity-specific measures of disability and outcomes in orthopaedic surgery. *J Bone Joint Surg Am* 2012 ; 94 : 277-285.
32. **Spitzer AB, Davidovitch RI, Egol KA.** Use of a "hybrid" locking plate for complex metaphyseal fractures and non-unions about the humerus. *Injury* 2009 ; 40 : 240-244.
33. **Yamane S, Suenaga N, Oizumi N, Minami A.** Interlocking intramedullary nailing for nonunion of the proximal humerus with the Straight Nail System. *J Shoulder Elbow Surg* 2008 ; 17 : 755-759.