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Treatment of presumed aseptic non-union of the humeral shaft by osteosynthesis combining intramedullary nailing and screw plate

B. VENDEVILLE, C. FABBRI, O. ROCHE, L. PEDUZZI, F. SIRVEAUX

Department of Orthopaedic and Traumatologic Surgery and Arthroscopy, Nancy, France.

Correspondence at: B Vendeville, Department of Orthopaedic and Traumatologic Surgery and Arthroscopy, 49 rue hermite, 54000 Nancy, France, Email: b.vendeville@hotmail.fr

In 2020, the most common treatment for presumed aseptic non-union of the humeral shaft seems to be decortication, often associated with bone autografting, and stabilized by a screw plate. We propose to evaluate an original technique of rigid osteosynthesis combining intramedullary nailing and screw plate. Between January 2004 and January 2020, 45 patients underwent treatment of presumed aseptic non-union of the humeral shaft by osteosynthesis combining intramedullary nailing and a screw plate. The minimum radio-clinical follow-up was one year postoperatively. The series included 19 men and 26 women with a mean age of 53 years (range 19-84 years). Bone consolidation was achieved in 43 patients, a rate of 95.5%. Comparing patients who achieved bone consolidation with the two failed consolidations did not reveal any statistically significant factor. Interobserver agreement was almost perfect (k=0.93) for the use of the RUST for humeral shaft fractures treated with intramedullary nailing and screw plate. In our study, the treatment of presumed aseptic non-union of the humeral shaft with an osteosynthesis combining intramedullary nailing and screw plate gives, with 95.5% of bone consolidation, results equal to or even superior to the different treatments currently described in the literature.

Keywords: non-union, nailing, plate, humerus.

INTRODUCTION

The literature describe a rate of humeral shaft non-union's occurrence between 0 and 13% after surgical treatment[1,2]. The risk factors found are multiple. They are linked to the patient (obesity, alcoholism and chronic smoking, unbalanced diabetes, osteoporosis), to the fracture's type (open, comminuted, transverse and short oblique, with loss of substance, septic), and to the surgical treatments already received (excessive devascularization, distraction of the fracture site, unstable osteosynthesis, inadequate postoperative immobilization)[1,3-6].

According to Gianoudis, the conditions for obtaining bone consolidation are the supply of osteogenic cells and growth factors associated with an osteoconductive matrix, attached by a mechanically stable osteosynthesis[3,4]. These conditions are more difficult to obtain when there have been previous surgical interventions[7].

In the current literature, multiple techniques are proposed for presumed aseptic humeral shaft non-union's treatment. They often combine decortication, frequently associated with a bone autograft, stabilized by a screw plate[1,8,9]. The absence of clinical, radiological, and biological criteria of infection at the time of care allows the presumed aseptic nature of the non-union to be established. Septic non-union requires specific treatment[10].

Our hypothesis is that intramedullary nailing avoids axis disorders by facilitating alignment of shaft's fragments, and that reaming is beneficial for bone consolidation. Using a plate helps to counteract rotational forces and to provide compression. Finally, bone grafting may be necessary in cases of significant local bone loss.

The goal of this study is to analyze the success rate of bone consolidation of presumed aseptic humeral shaft non-union when intramedullary nailing is combined with a screw plate, without increasing the complication rate.

MATERIALS AND METHODS

We conducted a descriptive, retrospective, monocentric study between January 2004 and January 2020 in the orthopedic surgery department of the Centre Chirurgical Emile Gallé, 54000 Nancy, France. Inclusion criteria were being at least 18 years of age and having a presumed aseptic non-union of the

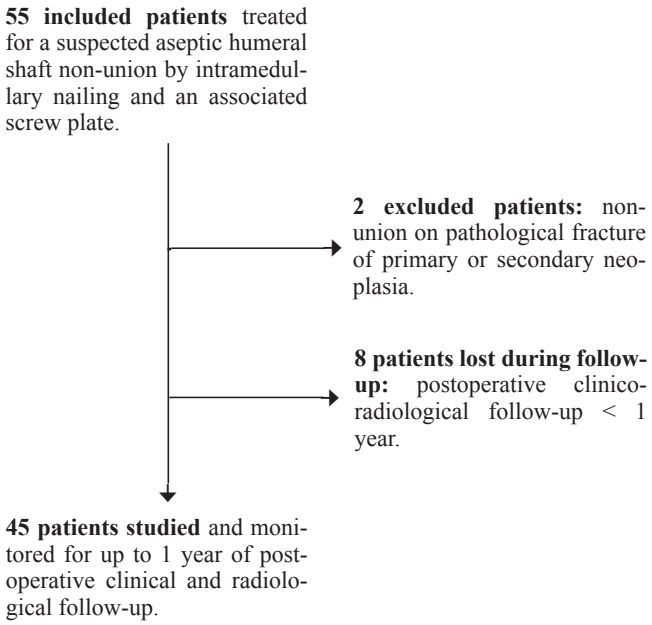

Figure 1. — Flow chart of study inclusion and exclusion criteria.

humeral shaft, previously operated or not. Exclusion criteria were proximal or distal metaphyseal non-union, pathological fractures, postoperative follow-up of less than one year. Fifty-five adult patients were treated for a presumed aseptic non-union of the humeral shaft with intramedullary nailing and an associated screw plate. Non-union was considered if radiological examinations showed no evolution of the consolidation process after at least 2 months after the last surgical or orthopedic treatment. Non-unions were presumed to be aseptic in the absence of clinical and biological signs of sepsis. Two patients were excluded from this study because they presented a non-union on a pathological fracture of primary or secondary neoplasia, and eight patients

Figure 2. — Patients with hypertrophic, oligotrophic or atrophic aseptic non-union of the middle part of the left humeral shaft.

Table I. — Demographic characteristics of patients

Parameters	Description
Number of patients studied n	45
Gender n (%) Male: n (%) Female	19 (20%): 26 (60%)
Average age in years	53 (range 19-84 years old)
Risk factor for non-union n (%)	
Smoker	17 (38%)
Alcohol drinker	3 (7%)
Diabetes	5 (11%)
Average BMI	27 (range 18,1-45 kg/m²)
Laterality (n (%) Right: n (%) Left)	23 (51%): 22 (49%)
Cause of fracture: n (%)	
Mechanical fall	33 (74%)
Road accident	8 (17%)
Crushing	2 (4%)
Direct trauma	2 (4%)
Fracture n (%) Closed: n (%) Open	40 (89%): 5 (11%)
Primary non-union n (%)	5 (11%)
Non-union after surgical treatment n (%)	40 (89%)
Number of patients who already had 1 surgery	21
Number of patients with 2 previous surgeries	12
Number of patients with 3 previous surgeries	5
Number of patients with 4 previous surgeries	2
Orthopedic treatment n (%)	5 (11%)
Last surgical treatment: n (%)	40 (89%)
Intramedullary nailing	11 (25%)
Screw plate	14 (31%)
Fasciculated pinning	15 (33%)
Type of non-union: n (%)	
Active hypertrophic	12 (27%)
Active oligotrophic	21 (46%)
Non active atrophic	12 (27%)

did not reach one year of postoperative follow-up. The study therefore included 45 patients (Figure 1). This study was initiated after the favorable opinion of the Committee for the Protection of Persons of the Clinical Research and Investigation Department of the Nancy Hospital and Regional University Center (number 2020PI187 21/08/2020).

The study included 26 women and 19 men with a mean age of 53 years (range 19-84). Seventeen were smokers, three were alcoholics and five were diabetics. The initial trauma was a mechanical fall in 33 patients,

a traffic road accident in eight, a crush injury in two, and a direct impact trauma in two. The initial fracture was open in five patients. Five (11%) patients had received orthopedic treatment and 40 (89%) had already had one to four iterative osteosyntheses. Amongst these 40 patients, 21 had already had one surgical intervention, and 19 patients had had at least two interventions. At the time of our care, 11 patients had intramedullary nailing in place, 14 had a lateral screw plate, and 15 had a fasciculated pinning. These surgical treatments resulted in five recovered radial palsies and three definitive radial palsies documented by electromyogram. The non-unions were classified according to the Weber and Cech classification[11,12]. Radiological analysis showed 12 active hypertrophic non-unions, 21 active oligotrophic non-unions and 12 non-active atrophic non-unions (Figure 2). The fracture site involved the upper part of the shaft in 17 patients, the middle part in 23 patients, and the lower part in five patients (Table I).

The patients are placed in a half-seated position under general anesthesia. A lateral approach to the humerus is performed on the non-union site, after identification, neurolysis and protection of the radial nerve. The osteosynthesis material already in place (nailing, plate, fasciculated pinning) is removed. The non-union site is excised with an oscillating saw and cancellous bone decortication is performed with a chisel. An intramedullary antegrade guide rod is inserted. The theoretical length of the nailing required to bridge the non-union site by at least three times the shaft diameter distally is measured under fluoroscopic control. Then an intramedullary reaming 1mm wider than the planned nailing diameter, ranging from 6.7 to 9.5mm. The small diameter antegrade intramedullary nailing is placed. Only proximal locking is performed, with the nailing ancillary instruments. This allows adjustment of distal rotation and compression of the distal fragment with the proximal fragment. The non-union site is grafted on 24 patients (53%) at this stage of the procedure before compression of the two fragments. Twelve patients were grafted with an iliac cancellous bone autograft, nine with bleeding cancellous bone shavings from the humeral end cuts, two with intramedullary reaming material, and one with a fragmented allograft. Excessive rotation is avoided by additional plate osteosynthesis. This plate is a short dynamic compression plate (DCP) of 3.5mm with six cortical screws on either side of the non-union site. It also allows compression of the two fragments on top of each other, or against the intercalated bone graft if performed. Multiple bacteriological samples were routinely taken in 31 patients (69%): 28 were negative and three were positive. In case of positive bacteriological samples, the patients were treated with an adapted dual antibiotic therapy for six weeks.

Patients were immobilized in a shoulder sling for an average of four weeks depending on clinical evolution.

Postoperative follow-up was performed regularly up to one year after the operation. It included a clinical evaluation of pain on active and passive mobilization of the shoulder and elbow, as well as direct palpation of the non-union site, logged in the patient's medical record. X-rays of the humerus from the front and the side were taken during each visit.

In our study, bone consolidation was assessed by combining a clinical criterion with indolence of the fracture site, and a radiological criterion with the formation of at least one cortical bone in continuity without signs of bone loosening.

As explained by Bhandari et al.[13], indolence on palpation of the fracture site is a widely used clinical criterion used to assess bone consolidation. The

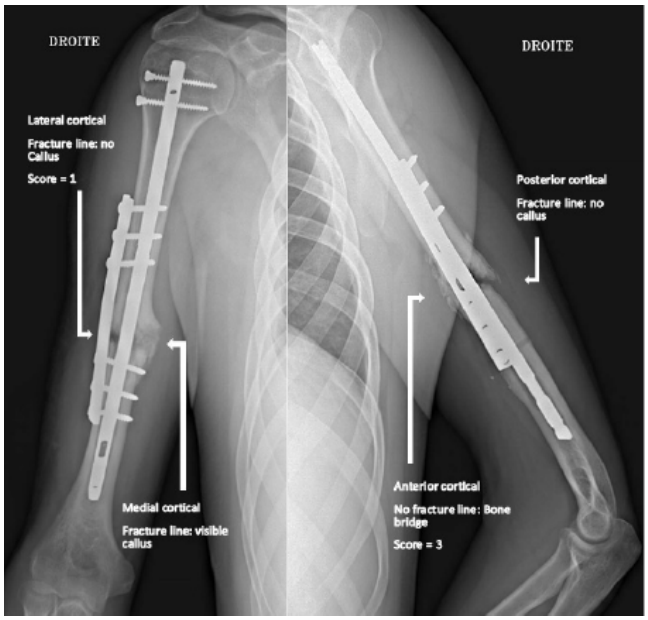

Figure 3. — Radiographic Union Score for Tibial Fractures (RUST) by Whelan et al. Frontal and lateral X-ray images of humerus after surgical treatment of aseptic non-union and osteosynthesis by intramedullary nailing and screw plate. RUST total score = 7.

Radiographic Union Score for Tibial Fractures (RUST)				
Cortical	**Fracture line: No callus (Score = 1)**	**Fracture line: Visible callus (Score = 2)**	**No fracture line: Bone bridge (Score = 3)**	***Total score: Minimum= 4 Maximum = 12***
Anterior				
Posterior				
Lateral				
Medial				

Table II. — Descriptive results of the achieved bone consolidation

Parameters	Description
Bone consolidation achieved n (%)	43 (95.5%)
Bone consolidation failure n (%)	2 (4.5%)
RUST at the end of the follow-up: n (%)	
= 4	2 (4.5%)
4 < RUST < 12	7 (15.5%)
= 12	36 (80%)

radiological bone bridge is assessed by a Radiographic Union Score for Tibial Fractures (RUST) strictly greater than four as described by Whelan et al.[14] (Figure 3). The RUST has been validated for nailed humeral shaft fractures[15]. In our study, a separate review of all X-rays by two orthopedic surgeons was performed to determine the reproducibility of the RUST for humeral shaft fractures treated with intramedullary nailing and screw plates.

A RUST of 4 more than one year after surgery without any other radiological evidence of bone consolidation progression was considered as a treatment's failure, with recurrence of non-union.

Secondary endpoints included the occurrence of complications associated with the surgical procedure.

The quantitative variables were described according to their dispersions, maximum and minimum values. Relationships between categorical variables were tested with the Fischer test. The significance level was set at 0.05.

A Cohen's Kappa test was used to assess the interobserver reproducibility of the RUST for humeral shaft fractures treated with intramedullary nailing and associated screw plate.

RESULTS

43 patients have bone consolidation after a one-year period a rate of 95.5%. At the end of the follow-up, 36 patients had a maximum RUST of 12, with four cortical in continuity (Table II), meaning 83.7% of the patients obtained bone consolidation (Figure 4).

In our study, interobserver agreement was almost perfect (k=0.93) according to Landis and Koch (16) for the use of the RUST on humeral shaft fractures treated with intramedullary nailing and screw plates.

At the end of a postoperative clinical and radiological follow-up, two patients still presented a non-union without evolution of the bone consolidation process on X-rays, with a RUST equal to four, confirmed by a CT scan.

These patients included a 32-year-old male smoker with an initially open fracture following a road accident, whose initial surgical care in another center for screw plate osteosynthesis was complicated by radial paralysis. Complete recovery of the radial nerve after neurolysis was obtained during a second surgical operation. The patient presented an atrophic non-union

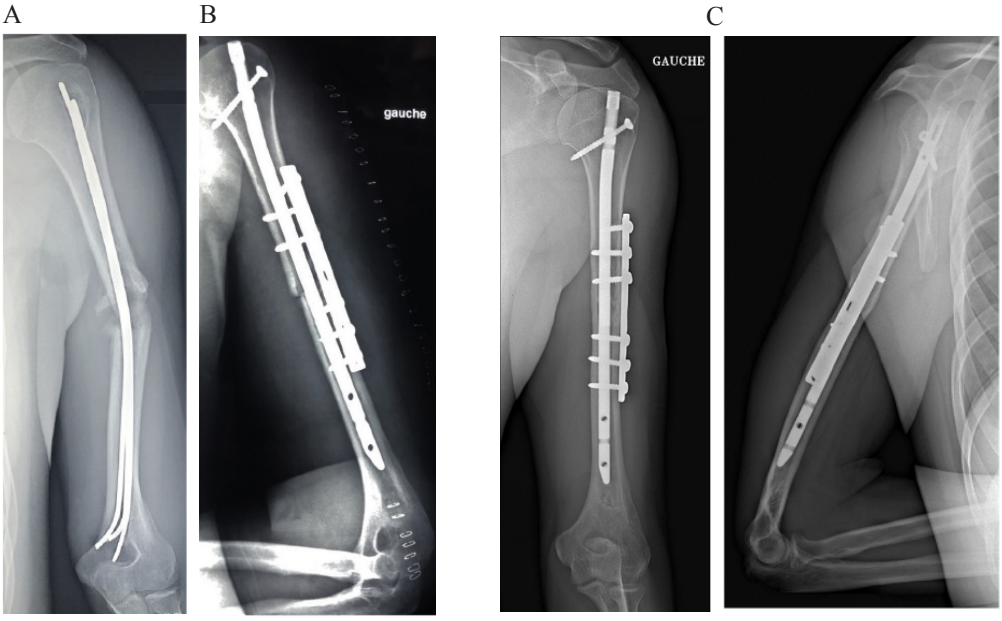

Figure 4. — A 23-year-old patient with a closed fracture of the middle part of the left humeral shaft from direct trauma. After an initial surgical treatment by fasciculated pinning, he presented at 12 months with an oligotrophic aseptic non-union of the middle part of the left humeral shaft. A) Preoperative X-rays, B) Immediate postoperative X-rays, C) X-rays at 24 weeks post-op. RUST=12.

of the middle part of the humeral shaft 16 months after the last surgical treatment. The patient was not grafted during our operation and the intraoperative samples came back positive for Staphylococcus Epidermidis and Cutibacterium Acnes. An adapted postoperative antibiotic treatment was implemented for six weeks. No clinico-biological signs of an active infectious process were found during the patient's follow-up. No radiological evidence of bone consolidation was found after more than one year.

The second patient was 43 years old and presented no risk factors for non-union. He presented a closed fracture of the middle part of the humeral shaft following a mechanical fall. Initial surgical management in another center with a screw plate was repeated after one year for non-union with a new osteosynthesis with a screw plate without bone graft. Eight months after, he still had an active hypertrophic non-union. The bleeding cancellous bone shavings from the humeral end cuts were grafted. No bacteriological samples were taken during surgery. No X-ray evidence of bone consolidation was observed more than one year after our procedure.

Therefore, these patients failed according to the criteria of bone consolidation chosen in this study. However, a new surgical procedure was not considered because of indolence, no functional limitation for the upper limb declared by the patient, and the absence of clinical and biological signs of an active infectious process in these two patients. B

The small number of failures does not allow us to identify a statistically significant factor for success or failure of bone consolidation. Among the failures, only one patient had a bone graft, which does not allow us to determine its influence on bone consolidation.

After the operation, three patients (6%) had a temporary radial paralysis, which fully recovered on its own within a few weeks.

In addition, three patients suffered from transient shoulder stiffness.

Finally, two patients underwent reoperation once bone consolidation had been achieved, for removal of the osteosynthesis material because of irritating pain in relation to the osteosynthesis material. One of these patients suffered pain from the proximal locking screw of the nail, and the other had discomfort on the lateral side of the arm in relation to the screw plate.

DISCUSSION

With a bone consolidation rate of 95.5%, this study shows that the treatment of presumed aseptic non-union of the humeral shaft by osteosynthesis combining intramedullary nailing and screw plate gives results in regards to bone consolidation that are equal to or even superior to the various current treatments[17].

The occurrence of failures and complications in our study allows us to identify its limitations. The surgical procedures were performed by several confirmed surgeons, inducing heterogeneity of the surgical technique. It thus seems interesting to study the benefit of a systematic bone graft. Indeed, Kontakis[18] shows in his meta-analysis that bone grafting remains a key factor in bone consolidation whatever the type of non-union (atrophic or hypertrophic) even if this point of view is not shared by the whole scientific community[19]. Furthermore, multiple systematic intraoperative bacteriological samples seem to be essential to search for an underlying septic cause, even in the absence of clinical or biological infectious signs. One likely cause of failed iterative non-union treatment may be the existence of an unrecognized associated bone infection, which is said to be present in 50 to 60% of recurrent non-union, depending on the series[7,20]. Moreover, our study is limited by its structure, since it is a retrospective descriptive study in which data derived solely from the patients' medical records. Thus, we have a regular but non-standardized radio-clinical follow-up of the patients. Similarly, data from standardized functional scores of the elbow and shoulder would allow evaluation of the active and passive functional results of the upper limb. The literature does not offer an analysis of bone loss and therefore of a possible difference in humeral length compared to the contralateral side, which seems interesting to study. The inclusion of a larger number of patients in the study would also increase its strength, although humeral shaft non-union remains an infrequent pathology.

This homogeneous series with a one-year follow-up is a strong point of this study. In addition, interobserver agreement after review of all X-rays by two orthopedic surgeons validates the use of the RUST to assess bone consolidation of humeral shaft fractures treated with intramedullary nailing and associated screw plates. Finally, the patients included in our study had often already undergone previous non-union treatments (42%). Few studies are currently proposing to study these patients with persistent non-union. In his series, Pollon et al.[7] found failure of bone consolidation in 25% of patients, requiring revision surgery. In our study, no patient was operated on again because of indolence and because no X-ray evidence of bone loosening around the osteosynthesis material was found.

Treatment of humeral shaft non-union by intramedullary nailing alone does not give satisfactory results[17]. In fact, the humerus is mainly subjected to torsional and distraction stresses and little axial stress, unlike the tibia and femur, which are in the weight-bearing zone[21-23]. Thus, the results of shaft non-union treatment after failed intramedullary nailing differ between the upper and lower limbs. While dynamization of tibial and femoral nails leads to consolidation, it is not effective in humeral shaft non-union. However, intramedullary nailing allows alignment of the shaft ends, and thus reduces sagittal and frontal axis disorders, especially in cases of significant loss of substance. In addition, systematic reaming before intramedullary nailing allows for the provision of growth factors that temporarily stimulate the consolidation process[19,24,25]. At the femoral level, several authors have shown that reaming before intramedullary nailing reduces bone consolidation time[26-28] and the rate of non-union occurrence[27,29]. However, intramedullary nailing alone is not sufficient. The addition of a short DC plate ensures stability against torsional forces[21] and compression. A plate with only six holes makes it possible to limit extensive dissection and its complications, including periosteal devascularization, as periosteal vascularization is an ally of the consolidation process[30]. With three bicortical screws on either side of the non-union site, our technique uses shorter plates than those described in other studies. Although Healy[31] suggests that plate fixation with at least three bicortical screws on either side of the non-union site is sufficient for stability, most studies suggest the use of long plates with at least four bicortical screws on either side[1,9,18,32-37] in order to obtain satisfactory stability. Some authors even suggest the association of two perpendicular plates to gain in stability[38-40]. In the upper limb, treatment by adding a plate to a pre-existing intramedullary nailing that has been left in place has been described by Gessmann[41]. He obtained a 97% consolidation rate in 37 patients. He explains that the combined extra- and intramedullary osteosynthesis provides increased stability while reducing the length of the plate used. However, by not changing the intramedullary nailing, he loses the benefit of reaming.

Thus, the combination of these two osteosynthesis systems at the humerus level seems justified to provide a mechanically stable environment as described by Frost[42], in accordance with the deformation theory of Perren[43,44], helping the process of bone consolidation[19,45]. The combination of intramedullary and extramedullary osteosynthesis has been described in the lower limb and has not shown negative effects on bone consolidation[46-49]. Although technically more demanding, bone grafting is possible in this surgical technique because the plate is short, and the diameters of the nail and screws are reduced. We did not determine any consensus criteria for the use of bone grafting. This was left to the judgment of the surgeon, depending on the loss of substance and the on-site condition. However, other studies observe higher consolidation rates when bone grafting is added[17]. In the previously described technique, antegrade nailing is used with a short superior-lateral approach and a short opening of the rotator cuff. This approach had already been chosen many times (n=11) for previous intramedullary nailing and we used it again for removal of the nails in place. Other studies describe complications associated with this approach, including retractile capsulitis and rotator cuff deficits[50]. However, as Wen et al explain in their meta-analysis[51], the superior-lateral approach of antegrade nailing does not result in statistically significant functional limitation of the shoulder and elbow compared to the lateral humeral approach used for the screw plate.

There are currently other techniques[9,12,17] with disparate results. In their meta-analysis, Peters et al.[17] study the existing techniques in 36 articles and include their results in terms of bone healing. Although no consensus has been reached, the most widely described and studied technique (in 17 articles evaluating 672 patients) is decortication, followed by bone autograft and osteosynthesis with a screw plate. It results in a consolidation rate of 98% (range 75-100%). The same technique but without associated bone grafting gives lesser results with a consolidation rate of 95% (range 75-100%). However, screw plate techniques are prone to complications, including radial nerve damage during dissection to access the non-union site in 6% of patients. As previously described, the nailing technique combined with bone grafting results in a lower rate of consolidation of about 88% (range 56-100%), falling to 66% (range 29-95%) if not combined with bone grafting. In addition to the causes of failure related to biomechanical problems already described, the radial nerve is affected almost 7% of the time during this procedure. The external fixator technique (with Ilizarov circular or monolateral fixator) combined with bone grafting results in a 98% consolidation rate (range 89-100%). El-Rosasy et al.[52] proposed an external fixator technique associated with intramedullary nailing in 18 patients, with 100% consolidation. These techniques are associated with radial nerve damage in only 3% of cases but are associated with infectious complications

in 9% of cases, compared with only 4% for screw-plate techniques and 3% for intramedullary nailing. In addition, external fixators are often poorly tolerated by patients[53].

There is currently no recommendation regarding dissection and possible transposition of the radial nerve for its protection.

CONCLUSION

In our study, the treatment of presumed aseptic non-union of the humeral shaft with an osteosynthesis combining intramedullary nailing and screw plate results in 95.5% bone consolidation, which is equal or even superior to the different treatments currently described in published studies.

It also has several advantages, including the use of plates to avoid torsional forces and to allow compression. The plates are short to limit extensive dissection and its deleterious effects on bone consolidation. Nailing also allows to fight against axis disorders. Finally, systematic intramedullary reaming before nailing seems to be an ally of bone healing.

This original work calls for a larger standardized study. We note the importance of systematic multiple intraoperative bacteriological samples and standardized clinical and radiological follow-up. Studying the benefit of systematic bone grafting and assessing the proper function of the shoulder and elbow before and after surgery also seems relevant. Finally, bilateral analysis of humerus lengths and substance loss, as well as induced axis and rotation disorders, seems relevant.

Conflict of interest: none declared.

REFERENCES

1. Singh AK, Arun GR, Narsaria N, Srivastava A. Treatment of non-union of humerus diaphyseal fractures: a prospective study comparing interlocking nail and locking compression plate. Arch Orthop Trauma Surg. juill 2014;134(7):947-53.
2. Sargeant HW, Farrow L, Barker S, Kumar K. Operative versus non-operative treatment of humeral shaft fractures: A systematic review. Shoulder Elb. août 2020;12(4):229-42.
3. Giannoudis PV, Einhorn TA, Marsh D. Fracture healing: the diamond concept. Injury. sept 2007;38 Suppl 4:S3-6.
4. Giannoudis PV, Gudipati S, Harwood P, Kanakaris NK. Long bone non-unions treated with the diamond concept: a case series of 64 patients. Injury. déc 2015;46 Suppl 8:S48-54.
5. Toh S, Tsubo K, Nishikawa S, Inoue S, Nakamura R, Harata S. Long-standing nonunion of fractures of the lateral humeral condyle. J Bone Joint Surg Am. avr 2002;84(4):593-8.
6. Hannouche D. Consolidation osseuse. In: Conference d'enseignement de la SOFCOT. Elsevier-Masson. Paris; p. 21-33.
7. Pollon T, Reina N, Delclaux S, Bonnevialle P, Mansat P, Bonnevialle N. Persistent non-union of the humeral shaft treated by plating and autologous bone grafting. Int Orthop. févr 2017;41(2):367-73.
8. Nandra R, Grover L, Porter K. Fracture non-union epidemiology and treatment. Trauma. janv 2016;18(1):3-11.
9. Volgas DA, Stannard JP, Alonso JE. Nonunions of the Humerus: Clin Orthop. févr 2004;419:46-50.
10. Ferreira N, Marais LC, Serfontein C. Two stage reconstruction of septic non-union of the humerus with the use of circular external fixation. Injury. août 2016;47(8):1713-8.
11. Weber BG, Čech O. Pseudarthrosen. Bern, Stuttgart: Huber; 1973.
12. Rupp M, Biehl C, Budak M, Thormann U, Heiss C, Alt V. Diaphyseal long bone nonunions – types, aetiology, economics, and treatment recommendations. Int Orthop. févr 2018;42(2):247-58.
13. Bhandari M, Guyatt GH, Swiontkowski MF, Tornetta P, Sprague S, Schemitsch EH. A Lack of Consensus in the Assessment of Fracture Healing Among Orthopaedic Surgeons: J Orthop Trauma. sept 2002;16(8):562-6.
14. Whelan DB, Bhandari M, Stephen D, Kreder H, McKee MD, Zdero R, et al. Development of the radiographic union score for tibial fractures for the assessment of tibial fracture healing after intramedullary fixation. J Trauma. mars 2010;68(3):629-32.
15. Misir A, Uzun E, Kizkapan TB, Yildiz KI, Onder M, Ozcamdalli M. Reliability of RUST and Modified RUST Scores for the Evaluation of Union in Humeral Shaft Fractures Treated with Different Techniques. Indian J Orthop. sept 2020;54(S1):121-6.
16. Landis JR, Koch GG. The measurement of observer agreement for categorical data. Biometrics. mars 1977;33(1):159-74.
17. Peters RM, Claessen FMAP, Doornberg JN, Kolovich GP, Diercks RL, van den Bekerom MPJ. Union rate after operative treatment of humeral shaft nonunion – A systematic review. Injury. déc 2015;46(12):2314-24.
18. Kontakis GM, Tosounidis T, Pagkalos J. Humeral diaphyseal aseptic non-unions: an Algorithm of management. Injury. mai 2007;38 Suppl 2:S39-49.
19. Elliott DS, Newman KJH, Forward DP, Hahn DM, Ollivere B, Kojima K, et al. A unified theory of bone healing and nonunion: BHN theory. Bone Jt J. juill 2016;98-B(7):884-91.
20. Masquelet AC. La technique de la membrane induite dans les reconstructions osseuses segmentaires: développement et perspectives. Bull Académie Natl Médecine. janv 2017; 201(1-3):439-53.
21. Blum J, Machemer H, Baumgart F, Schlegel U, Wahl D, Rommens PM. Biomechanical comparison of bending and torsional properties in retrograde intramedullary nailing of humeral shaft fractures. J Orthop Trauma. juill 1999; 13(5): 344-50.
22. Baltov A, Mihail R, Dian E. Complications after interlocking intramedullary nailing of humeral shaft fractures. Injury. janv 2014;45 Suppl 1:S9-15.
23. Flinkkilä T, Ristiniemi J, Hämäläinen M. Nonunion after intramedullary nailing of humeral shaft fractures. J Trauma. mars 2001;50(3):540-4.
24. Brinker MR, O'Connor DP. Exchange nailing of ununited fractures. J Bone Joint Surg Am. janv 2007;89(1):177-88.
25. Wenisch S, Trinkaus K, Hild A, Hose D, Herde K, Heiss C, et al. Human reaming debris: a source of multipotent stem cells. Bone. janv 2005;36(1):74-83.
26. Clatworthy MG, Clark DI, Gray DH, Hardy AE. Reamed versus unreamed femoral nails. A randomised, prospective trial. J Bone Joint Surg Br. mai 1998;80(3):485-9.
27. Selvakumar K, Saw KY, Fathima M. Comparison study between reamed and unreamed nailing of closed femoral fractures. Med J Malaysia. déc 2001;56 Suppl D:24-8.
28. Tornetta P, Tiburzi D. Reamed versus nonreamed anterograde femoral nailing. J Orthop Trauma. janv 2000;14(1):15-9.
29. Canadian Orthopaedic Trauma Society. Nonunion following intramedullary nailing of the femur with and without reaming.

Results of a multicenter randomized clinical trial. J Bone Joint Surg Am. nov 2003;85(11):2093-6.
30. Marenzana M, Arnett TR. The Key Role of the Blood Supply to Bone. Bone Res. sept 2013;1(3):203-15.
31. Healy WL, White GM, Mick CA, Brooker AF, Weiland AJ. Nonunion of the humeral shaft. Clin Orthop. juin 1987;(219): 206-13.
32. Babhulkar S, Babhulkar S, Vasudev A. Recalcitrant aseptic atrophic non-union of the shaft of the humerus after failure of surgical treatment: management by excision of non-union, bone grafting and stabilization by LCP in different modes. Injury. août 2017;48 Suppl 2:S33-43.
33. Ring D, Jupiter JB, Quintero J, Sanders RA, Marti RK. Atrophic ununited diaphyseal fractures of the humerus with a bony defect: treatment by wave-plate osteosynthesis. J Bone Joint Surg Br. août 2000;82(6):867-71.
34. Rubel IF, Kloen P, Campbell D, Schwartz M, Liew A, Myers E, et al. Open reduction and internal fixation of humeral non-unions : a biomechanical and clinical study. J Bone Joint Surg Am. août 2002;84(8):1315-22.
35. Cadet ER, Yin B, Schulz B, Ahmad CS, Rosenwasser MP. Proximal humerus and humeral shaft nonunions. J Am Acad Orthop Surg. sept 2013;21(9):538-47.
36. Livani B, Belangero W, Medina G, Pimenta C, Zogaib R, Mongon M. Anterior plating as a surgical alternative in the treatment of humeral shaft non-union. Int Orthop. oct 2010; 34(7):1025-31.
37. Rosen H. The treatment of nonunions and pseudarthroses of the humeral shaft. Orthop Clin North Am. oct 1990;21(4):725-42.
38. Rubel IF, Kloen P, Campbell D, Schwartz M, Liew A, Myers E, et al. Open reduction and internal fixation of humeral nonunions : a biomechanical and clinical study. J Bone Joint Surg Am. août 2002;84(8):1315-22.
39. Martinez AA, Cuenca J, Herrera A. Two-plate fixation for humeral shaft non-unions. J Orthop Surg Hong Kong. août 2009;17(2):135-8.
40. Prasarn ML, Achor T, Paul O, Lorich DG, Helfet DL. Management of nonunions of the proximal humeral diaphysis. Injury. déc 2010;41(12):1244-8.
41. Gessmann J, Königshausen M, Coulibaly MO, Schildhauer TA, Seybold D. Anterior augmentation plating of aseptic humeral shaft nonunions after intramedullary nailing. Arch Orthop Trauma Surg. mai 2016;136(5):631-8.
42. Frost HM. Bone «mass» and the «mechano-stat»: a proposal. Anat Rec. sept 1987;219(1):1-9.
43. Perren SM, Boitzy A. Cellular differentiation and bone biomechanics during theconsolidation of a fracture. Anat Clin 1978;28:13-28.
44. Perren SM. Physical and biological aspects of fracture healing with special refer-ence to internal fixation. Clin Orthop Rel Res 1979;138:175-195.
45. Ghiasi MS, Chen J, Vaziri A, Rodriguez EK, Nazarian A. Bone fracture healing in mechanobiological modeling: A review of principles and methods. Bone Rep. juin 2017;6:87-100.
46. Roetman B, Scholz N, Muhr G, Möllenhoff G. [Augmentive plate fixation in femoral non-unions after intramedullary nailing. Strategy after unsuccessful intramedullary nailing of the femur]. Z Orthopadie Unfallchirurgie. oct 2008;146(5): 586-90.
47. Birjandinejad A, Ebrahimzadeh MH, Ahmadzadeh-Chabock H. Augmentation plate fixation for the treatment of femoral and tibial nonunion after intramedullary nailing. Orthopedics. juin 2009;32(6):409.
48. Ueng SW, Chao EK, Lee SS, Shih CH. Augmentative plate fixation for the management of femoral nonunion after intramedullary nailing. J Trauma. oct 1997;43(4):640-4.
49. Choi YS, Kim KS. Plate augmentation leaving the nail in situ and bone grafting for non-union of femoral shaft fractures. Int Orthop. oct 2005;29(5):287-90.
50. Wang Y, Chen H, Wang L, Chen X, Zhi X, Cui J, et al. Comparison between osteosynthesis with interlocking nail and minimally invasive plating for proximal- and middle-thirds of humeral shaft fractures. Int Orthop. 12 nov 2020;
51. Wen H, Zhu S, Li C, Chen Z, Yang H, Xu Y. Antegrade intramedullary nail versus plate fixation in the treatment of humeral shaft fractures: An update meta-analysis. Medicine (Baltimore). nov 2019;98(46):e17952.
52. El-Rosasy MA. Nonunited humerus shaft fractures treated by external fixator augmented by intramedullary rod. Indian J Orthop. janv 2012;46(1):58-64.
53. Müller ME. Treatment of nonunions by compression. Clin Orthop. déc 1965;43:83-92.