20 Internal Fixation of Diaphyseal Humeral Fractures: Plate or Intramedullary Nail?

Michele James Ceglia, Stefano Bianco, Antonio Ciardullo, and Roberto Buzzi

20.1 Introduction

Humeral shaft fractures account for about 3 % of all fractures and 20 % of humeral fractures; therefore, they represent a common fracture in the adult [1, 2]. Most commonly they are represented by closed fractures: open fractures are 2–10 % of cases. Sixty percent involve middle third of the diaphysis.

Traditionally most humeral shaft fractures have been treated conservatively. The initial stabilization is usually achieved with a U-shaped splint. The splint is removed once swelling has subsided and a functional brace is applied [3]. Reduction occurs due to gravity and circumferential compression of the limb. The range of acceptable alignment of the fracture is quite wide [4] with up to 20–30° of angular and rotational deformities and up to 3 cm of shortening. With this treatment, encouraging results have been documented. Sarmiento et al. [3] reported an incidence of nonunion of less than 2 % in closed fractures and 6 % in open fractures. Time to union was 9 and 14 weeks in closed and open fractures, respectively. Varus deformity up to 10° was common and observed in 75–80 % of cases.

Also other authors have described positive outcomes of functional bracing. Koch et al. [5] retrospectively reviewed 67 humeral shaft fractures treated with a Sarmiento brace. Fifty-eight fractures (87 %) were clinically healed at a mean of 10 weeks after injury. Fifty-five cases treated conservatively (95 %) obtained an excellent or good clinical result. Three patients (5 %) had a slight limitation of active range of motion. All 58 patients returned to their job. Ekholm et al. [6] performed a retrospective study of 78 closed humeral shaft fractures. Ninety percent of the fractures healed with the brace. Almost 50 % of the patients reported full recovery. The short musculoskeletal functional assessment (SMFA) for arm/hand function was acceptable. The SF 36 score was slightly lower when compared to a Swedish reference population [6]. In conclusion, a high rate of union can be achieved with functional bracing, and these patients experience good functional outcome.

Not all diaphyseal humeral fractures can be treated conservatively, and absolute and relative indications to surgery have been defined [7, 8]. Intramedullary nailing (IMN) and plate fixation (PLT) techniques are the most common choices, and each one has advantages and disadvantages. Up to date there is an ongoing debate on whether treatment option is preferable. The purpose of this article is to describe the

M.J. Ceglia, MD (✉) • S. Bianco, MD
A. Ciardullo, MD • R. Buzzi, MD
Department of Traumatology and General Orthopaedics, AOU Careggi, Careggi Hospital, Largo Palagi 1, Florence 50139, Italy
e-mail: michaelceglia79@gmail.com

F. Castoldi et al. (eds.), *Simple and Complex Fractures of the Humerus*,
DOI 10.1007/978-88-470-5307-6_20, © Springer-Verlag Italia 2015

key points of such controversy as well as the data on which they are based.

20.2 Indications to Surgical Treatment

Surgical treatment is indicated in cases of failure to achieve and maintain acceptable reduction and alignment at fracture site. Bedridden patients and segmental fractures are examples. Open fractures require surgical treatment including debridement, lavage, and stabilization. Polytraumatized patients, fractures with articular extension either proximally or distally, associated fracture of the shoulder girdle or forearm benefit from surgical treatment to allow early motion and facilitate patient care. Humeral shaft fractures with a vascular injury require limb revascularization and stabilization. The presence of a nerve injury, more often regarding the radial nerve, may require nerve exploration and fracture stabilization. Pathological fractures are another good indication for surgery together with nonunions.

The growing importance of socioeconomic issues has expanded the indications for surgery. Some patients poorly tolerate the application of a brace. Others are concerned by the occasional occurrence of a malunion of the fracture. The possibility of active postoperative mobilization and of shorter sick leave also represents attractive advantages for some patients [9].

Operative techniques include plate fixation (PLT), intramedullary nailing (IMN), and external fixation. The choice depends on fracture characteristics, associated injuries, and surgeon's preference. Most surgeons use external fixators for acute fracture stabilization. Soft tissue injuries, burns, fractures in polytrauma patients, and associated vascular injuries are excellent indications for external fixation. The external fixator is usually converted to more stable constructs such as PLT or IMN.

Theoretically, both PLT and IMN have a rationale that justifies and favors their use. Topics of this debate include biologic insult, mechanical properties, as well as technical issues, results, and complications.

20.3 Plate and Screw Fixation

The theoretical advantages of plate and screw fixation include direct visualization, anatomic reduction, and compression of the fracture. Fracture gaps are poorly tolerated by the humerus and should be avoided. The radial nerve can be identified and explored. Neither the shoulder nor the elbow is harmed by the procedure therefore encouraging a full recovery of joint motion.

The disadvantages of PLT include a wide dissection, soft tissue stripping with biologic damage, and the potential for iatrogenic injury to neurovascular structures including the radial nerve.

The recommended surgical approach is influenced by the anatomic location of the fracture. The anterolateral approach is indicated in fractures of the proximal and middle third of the humeral shaft. It includes the deltopectoral approach which can be extended distally splitting the brachialis muscle in the middle [10]. The radial nerve is protected by the lateral third of the brachialis. The deltoid tendon requires to be elevated from the lateral surface of the humerus, but the consequences are limited if it is left continuous with the lateral half of the brachialis.

Fractures of the distal third are usually approached posteriorly; the advantage is a flat surface for the placement of the plate. There are different techniques to develop a posterior approach to the humerus. A triceps-splitting approach may be chosen: the lateral and long head of the triceps are separated proximally. The radial nerve may be visualized deep between the two heads. The deeper medial head is exposed and incised longitudinally. With the triceps-splitting approach and the mobilization of the radial nerve, 76 % of the humerus can be visualized [11]. Alternatively the triceps can be mobilized from lateral to medial, the so-called paratricipital approach. The lateral margin of the triceps is lifted off the lateral intermuscular septum. This approach avoids splitting the muscle and decreases scar formation and muscle denervation [12]. Using this approach over 90 % of humeral shaft can be exposed [11]. Regardless which approach is used, triceps splitting or paratricipital, the radial nerve must be identified and protected throughout the procedure.

Minimally invasive percutaneous osteosynthesis [13] technique has been recently developed for the treatment of humeral shaft fractures. The amount of soft tissue dissection is minimized compared to a traditional open approach. The approach is usually anterior with the arm maximally supinated to protect the posteriorly located radial nerve [14]. Excellent union rates without an iatrogenic injury to the radial nerve have been recently reported [13, 15].

The MIPO technique seems to enhance recovery of range of motion postoperatively [16]. Limited indications in terms of fracture type, increased technical difficulties, and prolonged use of fluoroscopy have so far limited this technique to spread among all surgeons.

As far as reduction techniques are concerned, indirect reduction is preferred to direct manipulation of bone fragments. Instruments with a small footprint like Weber clamps should be used whenever possible and preferred to more invasive instruments. The preliminary reduction is maintained with either K-wires or compression screws. A prominent screw head invariably interferes with the subsequent plate positioning. The use of smaller screws (2.4 or 2.7 mm in diameter) with low-profile heads adequately countersunk in the cortex is ideal to avoid interference with plate. Small plates applied with an antiglide function may be occasionally used to aid in preliminary reduction.

The type of fracture influences the plating technique: transverse and short oblique fractures should be plated with axial compression taking advantage of the oval shape of the holes. Prebending of the plate is mandatory to compress the opposite cortex. Alternatively the compressor device can be used but it requires a longer surgical approach. Oblique and spiral fractures can be treated with compression interfragmentary screws and a neutralization plate. Attention should be paid to minimize soft tissue dissection and interfragmentary screws should be placed through the plate if it all possible. Comminuted fractures are typically managed with bridge plating techniques to span the zone of comminution with minimal manipulation of the interposed bone fragments. A "wave plate" technique with autologous bone graft is advocated for the treatment of nonunions [17].

The most common implant employed is a narrow 4.5 mm straight plate. Smaller patients may require 3.5 mm plate. Fractures extended to the proximal metaphysis require plates with multiple locking screws to engage the humeral head. Fractures with extension to the distal metaphysis may require a preshaped plate with a "J" design to reach the lateral column of the distal humerus.

The ideal number of screws to be inserted on each fracture fragment is debated: two is the minimum, and three is wiser. This corresponds to six cortices to be engaged. More recent studies have emphasized that the working length of the plate may be more important than the number of screws [18, 19] and increased spacing between the screws may offer better mechanical properties. Nowadays the trend involves careful attention to optimal placement of the implants reducing at the same time the total amount of hardware.

The introduction of locking screws [20] has added a new dimension to the techniques, and this applies also to the treatment of humeral shaft fractures in the setting of osteoporosis. Plates are now available from many brands which accept both locking and non-locking screws, and locking screws may have a fixed or variable axis. Fixation with locking screws has been found to be mechanically superior to non-locking screws [21]. Hybrid fixation with a single non-locking screw and two locking screws has been found mechanically comparable to a fixation with three locking screws. Hybrid fixation offers some advantages in that the fracture can be preliminary reduced and compressed with the non-locking screws and then stabilized with locking screws [21]. The ideal number of locking screws has been investigated in the humeral shaft [22]. Other authors emphasized that two well-placed locking screws per fragment may offer sufficient mechanical stability which is not augmented by the placement of a third locking screw [22].

The advantage of the locking screws however seems to be less evident for fractures involving only the humeral shaft [23]. In conclusion until further data become available, locking screws may be advisable in osteopenic bone or nonunions or for a short proximal or distal fragment.

20.4 Intramedullary Nailing

Intramedullary nailing has theoretical advantages from a mechanical and biologic perspective.

Locked intramedullary humeral nails behave as load sharing devices [7] and promote the healing process without bone exposure at fracture site. IMN are positioned in line with the mechanical axis of the humeral shaft and therefore are subjected to lower bending loads.

Flexible nails including Kirschner wires or Ender nails have been used in the past, but they have been abandoned due to insufficient control of rotational and axial forces [24]. The main disadvantage of IMN is the production of an entry hole close to the proximal or distal epiphysis with possible pain and stiffness.

Currently the most common devices are represented by interlocking medullary nails which can be inserted in either an antegrade or a retrograde fashion.

To perform an antegrade nailing, the patient is positioned in either the beach-chair, supine, or lateral position. Antegrade nails are introduced through a deltoid-splitting incision followed by excision of the subdeltoid bursa and exposure of the supraspinatus tendon. The supraspinatus tendon is incised in line with its fibers in order to reach the correct entry point on bone surface. The insult to the rotator cuff may cause shoulder pain and stiffness [25].

The diameter of the medullary canal should be carefully evaluated preoperatively. The size of the nail should match the diameter of the medullary canal. The shape of the humerus is peculiar as it narrows along its course from proximal to distal and it ends 2 cm proximal to the olecranon fossa. The attempt to introduce a mismatched nail will invariably cause distraction at fracture site which predisposes to nonunion. Aggressive reaming to house an oversized nail has several potential drawbacks: cortical necrosis due to thermal injury [26], iatrogenic comminution at fracture site, and potential injuries to neurovascular structures.

Proximal locking should be performed before distal locking and it is preformed using the dedicated guide. Attention should be paid to the course of axillary nerve which runs about 5–6 cm distal to the acromion process. An oblique screw running proximal to distal is safer than a transverse screw. Before proximal locking, attention should be paid to avoid protrusion of the nail in the subacromial space in order to prevent postoperative shoulder impingement. After proximal locking, distraction at fracture site should be minimized. The fracture should be carefully reduced before proceeding to distal locking.

Distal locking is usually performed in the sagittal plane with “freehand” technique under fluoroscopic control. A 3 cm incision and two right angle retractors are useful to expose the bone and avoid accidental injuries to the soft tissues.

Retrograde nailing requires a prone position and triceps-splitting incision proximal to the olecranon. A substantial entry hole needs to be carefully produced proximal to the olecranon fossa and enlarged with high-speed burrs until it allows nail introduction. This procedure may significantly weaken the cortex of the distal humerus and predispose it to the feared complication of supracondylar fractures. Other possible complications include postoperative elbow pain and range of motion difficulties as well as the formation of periarticular ossifications. Distal locking is performed as previously described through the guide. Proximal locking is performed with “freehand” technique under fluoroscopic assistance usually in the frontal plane. Attention to avoid damage to neurovascular structures is essential also at this level.

20.5 Comparative Studies

A few comparative studies between PLT and IMN in diaphyseal humeral fractures have been published (Table 20.1).

Table 20.1 Randomized prospective studies of humeral shaft fracture fixation: intramedullary nails versus plates

Name, year	Patients	Time to healing	Nonunion	Infection	Postopeative radial nerve palsy	Shoulder problems	Elbow problems	Functional outcome	Complications	Second surgery
Chapman et al., 2000	84	Nonsignificant (ns)	ns	ns	ns	⇑ IMN	⇑ PLT	Not available (na)	ns	na
McCormack, 2000	44	(ns)	ns	ns	⇑ IMN	⇑ IMN	⇑ IMN	ns	⇑ IMN	⇑ IMN
Changulani, 2007	47	⇑ plate (PLT)	ns	⇑ PLT	⇑ PLT	ns	na	ns	⇑ PLT	na
Raghavendra, 2007	36	ns	ns	na	⇑ IMN	⇑ IMN	ns	⇓ IMN	⇑ IMN	⇑ IMN
Putti, 2009	34	ns	ns	ns	ns	ns	na	ns	⇑ IMN	ns
Khan, 2010	60	na	na	ns	ns	⇑ IMN	na	ns	na	na

Rodriguez-Merchan [27] prospectively studied 40 patients with closed transverse fractures of the diaphysis of the humerus without associated nerve palsies. All failed nonoperative treatment and were operated with either compression plating (PLT) or intramedullary fixation (IMN) with Hackethal nail. The patients were not randomized but the treatment was left to the surgeon's preference. The patients were reviewed with an average follow-up of 18 months. The patients in the IMN group required with one exception a second anesthesia to remove the symptomatic nails and had to be protected in the brace for 6 months. Patients in the PLT group performed the same rehabilitation protocol but did not use the postoperative brace. All fractures treated with IMN healed with a delayed union in one case. All the fractures treated by PLT healed with one exception who showed delayed union. The author concluded that there were no differences between the two groups and that either PLT or IMN can be used. Disadvantages of the IMN group included the need to use a postoperative brace and the need of a second procedure to remove the device.

Chapman et al. [28] performed a prospective randomized study including 84 patients which underwent IMN ($n=38$) or PLT ($n=46$). The devices implanted were either an antegrade humeral nail (Russell Taylor, Smith and Nephew) or a dynamic locking compression plate (DCP Synthes). The results were studied with a 13-month follow-up. Fracture healing by 16 weeks was present in 42 of 43 PLT, compared with 33 out of 38 in the IMN group (p=nonsignificant). Shoulder pain and decreased shoulder motion were significantly more frequent after IMN ($p=0.007$). A decreased range of motion of the elbow was significantly ($p=0.003$) more frequent after PLT of distal third fractures. The same patients did not experience increased elbow pain. The prevalence of other complications was not significantly different between the two groups. The authors concluded that both treatments can provide predictable methods for the treatment of these fractures.

McCormack et al. [29] prospectively randomized 44 patients with fractures of the shaft of the humerus to either intramedullary nail (IMN) or plating (DCP). After a minimum 6-month follow-up, there were no differences in shoulder and elbow function and pain and time to return to normal activity. Shoulder impingement was present in one case after plating and six after IMN. Complications were found in three DCP group patients compared with 13 in the IMN group. Secondary surgery was needed in 7 IMN nail patients but only one in the DCP group. The author concluded that DCP remained the best treatment for humeral shaft fractures, while IMN may have specific indications but is technically more demanding and shows a higher complication rate.

Changulani et al. [30] compared results of humerus IMN and DCP. Forty-seven patients with a diaphyseal fracture of the shaft were prospectively randomized. The IMN group included 23 patients, while in the DCP group there were 24 patients. Antegrade nailing was routinely employed and DCP plating was applied through an anterolateral or posterior approach. The outcome measurements included union time, union rate, functional outcome, and incidence of complications. Functional outcome assessed with the American Shoulder and Elbow Surgeons Score (ASES) showed no differences between the two groups. Union rate was similar, and time to union was significantly lower for IMN. Complications such as infection were higher with DCP. Shortening of the arm and restriction of shoulder movements due to impingement were more frequent with IMN compared with DCP. The authors concluded that IMN may be preferable because of shorter union time and lower incidence of infection. There were no differences between the two groups in terms of rate of union and functional results.

Raghavendra and Bhalodiya [31] prospectively studied 36 patients with fractures of the shaft of the humerus. The follow-up was from 1 to 2 years. There were two groups, each one of 18 patients. There were no differences in union time between the two groups but patients with an interlocking nail underwent more bone grafting procedures to achieve the union (six vs two). A good to excellent result was achieved by 12 patients in the DCP (66 %) compared to 4 patients

(25 %) in the nailing group. Locked nailing was associated with a significant reduction of shoulder function ($p = 0.003$) and overall results ($p = 0.02$). The authors concluded that there was no difference between the two groups in terms of time to union. However compression plating was preferable because of better preservation of joint function and lesser need for secondary bone grafting.

Putti et al. [32] randomized 34 patients with humeral shaft fractures to either antegrade IMN ($n = 16$) or DCP ($n = 18$). Fractures were classified according to the AO system (type A in 19 cases, type B in 15 cases). The outcome evaluation included functional results, union, and complications. The minimum follow-up was 24 months. The functional scores according to American Shoulder and Elbow Surgeons (ASES) were not significantly different. Complication rates were higher in IMN group versus DCP groups (50 % vs 17 %, $p = 0.038$) and the nonunion rate was 0 % versus 6 % (ns). Two patients in the IMN group sustained an iatrogenic fracture at the time of insertion. Two had a radial nerve palsy and one patient needed nail removal for shoulder impingement. Three patients had adhesive capsulitis. The authors concluded that the complication rate was higher in the IMN group, while functional outcomes were similar in the two groups.

Khan et al. [33] compared two groups of 30 patients each treated with intramedullary interlocking nail and plating with DCP. In the IMN group 11 patients had moderate to severe shoulder dysfunctions and 8 of them were above 50 years of age. In the DCP group only one patient had severe shoulder dysfunction ($p = 0.001$). There was no significant difference in infection rate and palsy between the two groups. The authors concluded that antegrade nailing may not be suitable in elderly patients as it can cause significant shoulder dysfunction.

20.6 Meta-Analysis

In an effort to enlarge the number of patients, several meta-analysis have been performed (Table 20.2).

Bhandari et al. [16] reviewed randomized trials from 1969 to 2000. Only three studies were included for a total of 155 patients. Plate fixation showed a lower risk of reoperation compared to the intramedullary nailing. The risk reduction was 74 %: one reoperation could be prevented every ten patients treated with plates. Plate fixation also reduced the risk of shoulder problems. The authors concluded that plate fixation may reduce the risk of reoperation and shoulder impingement.

Orthopedic Trauma Directions in 2007 performed a meta-analysis based on a MEDLINE search for randomized and quasi randomized studies published between 1995 and 2007. Three studies were identified. Common outcome measures included reoperation (any additional humeral surgery), nonunion, time to union, infection, and nerve injury. The authors identified an

Table 20.2 Meta-analysis of randomized prospective studies of humeral shaft fracture fixation: intramedullary nails versus plates

Author, year	Total complication rate	Reoperation	Time to union	Nonunion	Shoulder problems	Radial nerve palsy
Bhandari, 2006	Not available (na)	⇑ IMN	na	ns	⇑ IMN	ns
Orthop Tr Directions, 2007	na	⇑ IMN	ns	ns	na	ns
Orthop Tr Directions, 2010	na	⇑ IMN	ns	ns	na	⇑ IMN
Heineman, 2010	Nonsignificant (ns)	ns	ns	ns	na	ns
Heineman, 2010	⇑ nail (IMN)	ns	ns	ns	na	ns
Ouyang, 2013	na	⇑ IMN	na	ns	⇑ IMN	ns

increased risk of reoperation with IMN. Time to union ranged from 6.3 to 9.8 in the IMN group compared with 8.9–10.4 of the plating, and the difference was significant in only one study.

This study was updated by Orthopedic Trauma Direction in 2010 by adding the fourth study carried out by Putti et al. Outcome measures remained the same. There was a significantly increased incidence of reoperation and radial nerve palsy after IMN, while the time to union remained not significant.

Heineman et al. [34] performed a literature search between 1967 and 2007 in the main medical search engines. Four randomized trials were selected pooling a total of 203 patients. Primary outcome included the total complication rate. Secondary outcomes included nonunion, infection, nerve palsy, and reoperation rate. Results did not show significant differences between the IMN and PLT groups. These authors updated their conclusions adding Putti's study and found that total complication rates were higher after IMN nailing [35].

Ouyang et al. [36] conducted an updated meta-analysis on the optimal treatment of humeral shaft fractures and included ten randomized controlled trials comparing nailing and plating from 1969 to 2011. Primary outcomes were nonunion, delayed union, postoperative infection, reoperation, and radial nerve palsy. Secondary outcomes include shoulder motion, shoulder impingement, iatrogenic fracture comminution, and implant failure. Plating (PLT) reduced the risk of shoulder impingement and shoulder loss of motion in comparison to nailing (IMN). Reoperation risk was uncertain. No other significant difference was identified. The authors concluded that plating and nailing can achieve similar results, but plating may reduce the occurrence of shoulder problems.

Conclusion

The classic indications to surgical treatment of diaphyseal fractures of the humerus have broadened due to new considerations including cost-effectiveness, time of disability, functional outcome, and others [20]. Given this trend it would be helpful to define which surgical option, PLT or IMN, represents the gold standard technique.

Both plates and nails have relative advantages and disadvantages. IMN seems to be ideal from the biologic point of view since the technique may be employed without exposing the fracture site. The cosmetic advantage of IMN is also obvious. A disadvantage to be expected with IMN is the increased incidence of pain and stiffness at the site of introduction of the nail, namely, the shoulder or the elbow.

Plating techniques offer the opportunity to visualize fracture fragments and to manipulate these to achieve a more anatomic reduction of the fracture. If exploration of the radial nerve is needed, the use of a plate seems logical. The obvious disadvantage of plating is the wide dissection to be employed which can lead to a biologic insult and delayed healing.

Both techniques are demanding and require a careful operative execution. Technical difficulties are challenging to estimate and may be widely influenced by the surgeon's training and experience.

The type of fracture also has an influence on the choice of the procedure. When the fracture approach is to either the proximal or distal epiphysis, a plating technique is advisable. Segmental, comminuted, and pathological fractures are good indications for IMN; again the presence of a short proximal or distal fragment demands the use of a plate. The presence of a preoperative radial nerve palsy suggests avoidance of closed IMN for fear of further damage to the nerve.

The revision of comparative randomized trials between PLT and IMN suggest that significant differences occur (Table 20.1). We pooled six publications for a total 305 patients. We analyzed differences in 9 outcome measures for a total of 54 fields. We found that 25 (46 %) fields showed insignificant differences. A significant difference was identified in 18 (33 %) fields: in 14 (26 %) fields IMN performed less well, while in 6 (11 %) PLT was inferior. Differences in eight (15 %) fields could not be evaluated because data were not available. The results of meta-analysis (Table 20.2) further contribute to identification of significant differences. We pooled 6 meta-analysis and analyzed 6 outcome measures for a total of 36 fields. There were no differences in 18 (50 %) fields, while a significant difference was shown in eight (22 %), and IMN performed less well in all of them. Differences in ten (28 %) fields could not be evaluated because data were not available. Significant differences seem to suggest that IMN perform less well with increased incidence in reoperation rate, radial nerve palsy, and shoulder problems.

In conclusion published trials have been limited in size and have methodological limitations. Definitive larger trials should be conducted and should be prospective randomized with blinding of patients, care providers, and outcome assessors. The influence of new devices including locked plating and newly designed intramedullary nails along with the importance of new surgical techniques like MIPO should also be evaluated.

References

1. Tytherleigh–Strong G (1998) The epidemiology in humeral shaft fractures. J Bone Joint Surg Br 80(2):249–253
2. Igbigbi PS (2004) Epidemiology of humeral fractures in Malawi. Int Orthop 28:338–341
3. Sarmiento A, Zagorsky JB, Zych GA et al (2000) Functional bracing for the treatment of fractures of the humeral diaphysis. J Bone Joint Surg Am 82(4):476–488
4. Klenerman L (1966) Fractures of the shaft of the humerus. J Bone Joint Surg Br 48(1):105–111
5. Koch PP, Gross DF, Gerber C (2002) The results of functional bracing of humeral shaft fractures. J Shoulder Elbow Surg 11(2):143–150
6. Ekholm R, Tidermark J, Törnkvist H, Adami J, Ponzer S (2006) Outcome after closed functional treatment of humeral shaft fractures. J Orthop Trauma 20(9):591–596
7. Schemitsch EH, Bhandari M (1998) Fractures of the humeral shaft. In: Browner J, Levine T (eds) Skeletal trauma. Saunders, Philadelphia, pp 1481–1511
8. Rommens PM, McCormack R (2007) Humerus, shaft. In: Ruedi T, Buckley RE, Moran CG (eds) AO principles of fracture management. AO publishing, Davos Platz, pp 595–597
9. Bhandari M, Devereaux PJ, McKee MD, Schemitscch EH (2006) Compression plating versus intramedullary nailing of humeral shaft fractures – a meta-analysis. Acta Orthop 77(2):279–284
10. Hoppenfield S, deBoer P (2003) Surgical exposures in orthopaedics: the anatomic approach, 3rd edn. Lippincott Williams and Wilkins, Philadelphia
11. Gerwin M, Hotchkiss RN, Weiland AJ (1996) Alternative operative exposures of the posterior aspect of the humeral diaphysis with reference to the radial nerve. J Bone Joint Surg Am 78(11):1690–1695, Gerwin 1996
12. Zlotolow DA, Catalano LW III, Barron OA, Glickel SZ (2006) Surgical exposures of the humerus. J Am Acad Orthop Surg 14(13):754–765
13. Zhiquan A et al (2007) Minimally invasive plating osteosynthesis (MIPO) of middle and distal third humeral shaft fractures. J Orthop Trauma 21:628–633
14. Apivatthakakul T et al (2005) Minimally invasive plate osteosynthesis (MIPO) of the humeral shaft fracture. Is it possible? A cadaveric study and preliminary report. Injury 36:530–538
15. Jiang R, Luo CF, Zeng BF, Mei GH (2007) Minimally invasive plating for complex humeral shaft fractures. Arch Orthop Trauma Surg 127(7):531–535
16. Kobayashi M, Watanabe Y, Matsushita T (2010) Early full range of shoulder and elbow motion is possible after minimally invasive plate osteosynthesis for humeral shaft fractures. J Orthop Trauma 24(4): 212–216
17. Hsu TL, Chiu FY, Chen CM, Chen TH (2005) Treatment of nonunion of humeral shaft fracture with dynamic compression plate and cancellous bone graft. J Chin Med Assoc 68(2):73–76
18. Crow BD, Mundis G, Anglen JO (2007) Clinical results of minimal screw plate fixation of forearm fractures. Am J Orthop 36(9):477–480
19. Lindvall EM, Sagi HC (2006) Selective screw placement in forearm compression plating: results of 75 consecutive fractures stabilized with 4 cortices of screw fixation on either side of the fracture. J Orthop Trauma 20(3):157–162
20. Walker M et al (2011) Humeral shaft fractures: a review. J Shoulder Elbow Surg 20(5):833–844
21. Gardner MJ et al (2006) Hybrid locked plating of osteoporotic fractures of the humerus. J Bone Joint Surg Am 88(9):1962–1967
22. Hak DJ et al (2010) Locked plate fixation of osteoporotic humeral shaft fractures: are two locking screws per segment enough? J Orthop Trauma 24(4):207
23. O'Toole RV et al (2008) Are locking screws advantageous with plate fixation of humeral shaft fractures? A biomechanical analysis of synthetic and cadaveric bone. J Orthop Trauma 22(10):709–715
24. Zimmerman MC, Waite AM, Deehan M, Oppenheim W (1994) A biomechanical analysis of four humeral fracture fixation systems. J Orthop Trauma 8(3): 233–239
25. Cheng HR, Lin J (2008) Prospective randomized comparative study of antegrade and retrograde locked nailing for middle humeral shaft fracture. J Trauma 65(1):94–102

26. Leunig M, Hertel R (1996) Thermal necrosis after tibial reaming for intramedullary nail fixation. J Bone Joint Surg Br 78-B:584–587
27. Rodriguez-Merchan EC (1995) Compression plating versus Hackethal nailing in closed humeral shaft fractures failing nonoperative reduction. J Orthop Trauma 9(3):194–197
28. Chapman JR, Henley MB, Agel J, Benca PJ (2000) Randomized prospective study of humeral shaft fracture fixation: intramedullary nails vs plates. J Orthop Trauma 14(3):162–166
29. McCormack RG, Brien D, Bucley RE, McKee MD et al (2000) Fixation of fractures of the shaft of the humerus by dynamic compression plate or intramedullary nail. J Bone Joint Surg Br 82-B:336–339
30. Changulani M, Jain UK, Keswani T (2007) Comparison of the use of the humerus intramedullary nail and dynamic compression plate for the management of diaphyseal fractures of the humerus. A randomized controlled study. Int Orthop 31:391–395
31. Raghavendra S, Bhalodiya H (2007) Internal fixation of fractures of the shaft of the humerus by dynamic compression plate or intramedullary nail: a prospective study. Indian J Orthop 41(3):214–218
32. Putti AB, Uppin RB, Putti BB (2009) Locked intramedullary nailing versus dynamic compression plating for humeral shaft fractures. J Orthop Surg (Hong Kong) 17(2):139–141
33. Khan AS, Azfal W, Anwar A (2010) Comparison of shoulder function, radial nerve palsy and infection after nailing versus plating in humeral shaft fractures. J Coll Physicians Surg Pak 20(4):253–257
34. Heineman DJ, Poolman RW, Nork SF, Ponsen KJ, Bhandari M (2010) Plate fixation or intramedullary fixation of humeral shaft fractures. Acta Orthop 81(2):216–223
35. Heineman DJ, Bhandary MO et al (2010) Treatment of humeral shaft fractures – meta-analysis reupdated. Acta Orthop 81(4):517
36. Ouyang H, Xiong J, Xiang P, Cui Z, Chen L, Yu B (2013) Plate versus intramedullary nail fixation in the treatment of humeral shaft fractures: an updated meta-analysis. J Shoulder Elbow Surg 22: 387–395