Lo SCALPELLO (2021) 35:39-48
doi number: 10.36149/0390-5276-199

Plate osteosynthesis of proximal humerus fractures: treatment options and technical advancements

Paolo Paladini[1], Antonio Padolino[1], Giovanni Merolla[1,2], Carlo Alberto Augusti[1], Giuseppe Sircana[1,3]

[1] Unit of Shoulder and Elbow Surgery, Cervesi Hospital, Cattolica, Italy; [2] International Doctorate School (PhD) in Clinical and Experimental Medicine, Italy; [3] Unit of Orthopaedics and Traumatology, Ceccarini Hospital, Riccione, Italy

Summary

Proximal humerus fractures are the third most common fracture in the elderly, producing an impressive social and economic burden. Their treatment is still controversial in the literature, with unconclusive evidence regarding the best therapeutic choice. Osteosynthesis with locking plates is considered the main surgical treatment, providing good clinical and radiographic outcomes over solid biomechanical bases, even if high complication rates have been reported. The main complications are intra-articular screw penetration, varus collapse, and avascular necrosis of the humeral head. In order to reduce the complication rate, it is necessary to correctly select patients who are suitable for surgical treatment; provide an adequate reduction of the fracture; effectively address medial hinge disruption; avoid complications related low bone quality. Many technical options to achieve better results have been developed, ranging from design modification to allograft augmentation. The aim of this review is to provide up-to-date information to aid the surgeon in choosing the correct treatment for the individual patient.

Key words: proximal humerus fracture, locking plate, CF-PEEK plate

Received: March 5, 2021
Accepted: March 15, 2021

Correspondence
Giuseppe Sircana
Unit of Shoulder and Elbow Surgery, Cervesi Hospital, AUSL Romagna, via L. v. Beethoven 46, 47841 Cattolica, Italy. Tel. +39 0541 966 382. Fax +39 0541 966 312. E-mail: gsirca@hotmail.it

Conflict of interest
The authors have no conflict of interest to declare.

How to cite this article: Paladini P, Padolino A, Merolla G, et al. Plate osteosynthesis of proximal humerus fractures: treatment options and technical advancements. Lo Scalpello Journal 2021;35:39-48. https://doi.org/10.36149/0390-5276-199

Introduction

Proximal humerus fractures (PHF) account for 4-5% of all fractures and are the third most common fracture in the elderly after hip and distal radius fractures [1,2]. The mean incidence is 63-105 cases per 100,000 person-years [2-4], and a 63% increase in incidence has been observed from 1970 to 2002 [4]. Females are 2.42 times more at risk to undergo a PHF [2]; mean age is 68.8 years [5] and the incidence increases with age in both sexes [2,4]. The most commonly reported etiology is a fall from standing height [2].

PHF produce an impressive social and economic burden, as they cause inability in activities of daily living and, therefore, impose the need for support in previously independent individuals [6]; hospitalization is often required, with yearly healthcare related costs estimated to reach € 33.6 million [7], with mortality during hospitalization reaching 1.1% [7] and rising to 7.83% within one year after the injury, which is 5.2 times higher than general population [5]. Therefore, appropriate treatment of these fractures is of paramount importance to restore shoulder function and independence to treated patients and to avoid complications.

The aim of this review was to report the indications, surgical options, and complications of plating for PHF.

Fracture classification

Various classifications for PHF have been described [8-10], yet none proved to be definitive. Neer's four-segment classification is the most commonly used by surgeons in clinical practice, followed by Hertel's binary description system and AO classification, which give more details on the pattern of PHF but are more complicated to analyze [11]. All these classifications are built on a common basis, classifying the fracture by number and characteristics of bone parts generated by the fracture lines; Codman [12] first described five basic fracture planes that could be reproducibly identified in PHF. Combining these fracture planes, multiple theoretical fracture patterns can be obtained, dividing the proximal humerus in four major segments: the lesser tuberosity, the greater tuberosity, the articular surface, and the humeral shaft. Thus, he created the four-part model that inspired subsequent classifications.

Neer [8], following Codman's observations, defined the four-segment classification system. This classification is based on the presence of displacement of one or more of the four major segments. Displacement of a part is defined as angulation of more than 45° or separation of more than 1 cm. This allows to group together all undisplaced or minimally displaced fractures, regardless of the number and path of fracture lines, and to focus the surgeon's attention on displaced fractures. Being based on displacement, this classification highlights the effect of muscle attachments on each segment and evaluates the consequences of displacement on vascularity and articular surface. Fractures were classified as: one-part fractures (minimal displacement), two-part articular segment displacement (anatomic neck), two-part shaft displacement (surgical neck), two-part greater tuberosity displacement, two-part lesser tuberosity displacement, three-part displacements, four-part fractures, fracture-dislocations and articular surface defects [13]. Unfortunately, the classification alone cannot guide treatment, as the patient's characteristics and available treatment methods must be taken into consideration [13].

Hertel et al. [9] proposed a classification based on modified Codman's fracture planes: they believed that the tuberosities should be considered as an intercalated segment between the head and the shaft. For descriptive purposes, the four segments were imagined as four Lego blocks that could be separated from each other. The various combinations of these Lego blocks produced 12 possible fracture patterns. This resulted in 6 fracture patterns dividing the proximal humerus in 2 parts, 5 dividing it in 3 parts, and 1 dividing it in 4 parts. The surgeon must answer 5 yes/no questions and, based on the answer, the fracture will fall into one of the 12 categories. Because of those dichotomous questions, the method was named "binary description system" and the authors claimed that it is easy to teach an apply, providing clear-cut diagnostic subgroups. The main focus of this classification is the assessment of ischemia: 5 fracture types were identified that carried an higher risk of humeral head ischemia; in all, there was displacement of the head segment [9].

AO classification [10], in its latest revision, divides PHF in three types: A. fractures, extraarticular, unifocal, 2-part fracture; B. fractures, extraarticular, bifocal, 3-part fracture; C. fractures, articular or 4-part fracture. Each type comprises further subgroups, and a total of 27 subgroups are described. This classification takes into account fracture patterns, mechanism of dislocation, and risk of head ischemia, but it is complex and rarely of use in clinical practice [11].

Despite the effort to create clear categories and to provide clear information for sorting, all these classifications, when tested, showed unsatisfactory reproducibility. Substantial agreement can be found for Neer's classification, but with a wide range of results among authors (k 0.33-0.70) [14-21]; fair to moderate agreement could be demonstrated for the AO classification (k 0.31-0.59) [15,16,19,21], while Hertel's classification showed moderate to substantial correlation (k 0.39-0.63) [17,20], with better results when CT assessment was performed, despite not being significantly better than Neer's classification on direct comparison [20]. Neer commented on these results, depicting the difficulties in correctly classifying fractures: exacting radiographic studies, surgeon's knowledge and experience and, often, intraoperative exploration are needed to correctly classify the fracture and, consequently, plan the correct treatment [13]. Surprisingly, higher agreement was shown on treatment choice than on fracture classification, despite not exceeding a moderate agreement [14,18,22]. In those cases when agreement was higher, better outcomes were obtained [22]. Correlation of one classification with another is controversial: translation cannot be directly done, but single radiographs need to be reassessed [23].

Treatment

No consensus has been reached on the optimal treatment of PHF. While undisplaced fractures are unanimously treated conservatively with good outcomes [11,24], the treatment of displaced fractures remains controversial: the lowest agreement is in three- and four-parts fractures [11]. According to the analysis of a large population, 49% of PHF are undisplaced and 28% are 2 part fractures. This leaves 23% of fractures in which a high grade of uncertainty exists. The lack of consensus on treatment is confirmed by the variation in surgical procedure rates among different regions [25,26]. Only moderate agreement exists among surgeons regarding treatment choice [14,18,22], decreasing to fair when evaluators are inexperienced surgeons [22].

Treatment options range from non-operative to plating, pinning, nailing, hemiarthroplasty, and reverse total shoulder arthroplasty [27-29]. In this review, we discuss the various technical options for plate fixation.

In a multicenter study comparing surgical versus conservative treatment for displaced PHF (PROFHER trial), no difference was found between groups in patient-reported outcome measurements [27]. Similar results were reported in a 5-year follow-up study [30]. Therefore, the authors claimed that surgical treatment of PHF generates high costs without providing health benefits [31] and concluded that the increasing trend for surgical treatment was not supported by evidence [27]. Similar findings were reported by other authors, who compared the outcomes of conservative and surgical treatment in elderly patients [28,32]. Furthermore, plate osteosynthesis in the elderly tends to have high failure rate, up to 34% [33], increasing with age and fracture complexity [33]. A recent meta-analysis comparing conservative treatment and plate fixation showed no clinical differences, higher rate of non-unions with conservative treatment, and higher rate of reoperations with surgical treatment [34]. The results of the PROFHER trial prompted clinicians to prefer conservative treatment [35], but this choice is debatable. The PROFHER trial excluded patients with a clear indication for surgery, providing useful information for borderline and uncertain cases. Furthermore, information about the surgeons' experience and operative techniques, stability of fixation, and radiographic outcomes are lacking [36,37]. Thus, careful preoperative planning and surgeon's evaluation can give good clinical outcomes and minimize the risk of perioperative and postoperative complications, even in elderly patients [38,39]. On the other hand, surgeons need to be aware that surgical treatment after failed conservative treatment and revision surgery provide worse clinical results than primary surgery [29,40].

Surgical treatment should be recommended in the following conditions: three- or four-part fracture dislocations, head-splitting fractures, pathological fractures, open fractures, severe ipsilateral injuries to the shoulder girdle, and fractures involving the attachments of the rotator cuff tendons and associated neurovascular injuries [41,42]. The choice whether to undergo surgery is often left to surgeon's experience and beliefs. Several variables can affect the type of surgical treatment [13], including age and medical conditions of the patient, involved side, functional requirements of the patient, bone quality, surgeon's experience, associated neurovascular injuries, and ability of the patient to effectively participate in the rehabilitation protocol [11].

Age is the main factor associated with the risk of failure after plate fixation, and therefore caution is needed when indication for plating is given to individuals aged more than 65 years. Unfortunately, the incidence of PHF increases with age and the majority of patients will be over 65 years [2,4,5]. Patients with higher requirements will benefit more from surgical treatment. Among patients aged 65 or older suffering from a PHF, 38% were, at least in part, dependent and 9% would become so after treatment[6], hindering participation in the rehabilitation protocol.

Poor bone quality in elderly individuals, increases the risk of impaction, loss of reduction, and failure of the implant, whereas good bone quality facilitates reduction and prevents screw cut-out [43,44]. Evaluation of bone mineral density prior to the operation can, therefore, be of aid in foreseeing complications. It can be reliably measured on preoperative standard X-rays with the deltoid tuberosity index [43]. This index is the ratio between the outer cortical diameter and inner endosteal diameter measured on an anteroposterior radiograph directly proximal to the deltoid tuberosity, where the outer cortical borders become parallel. Values lower than 1.4 predict low bone mineral density of the humeral head [43].

Plate fixation

Before introduction of locking plates, internal fixation of PHF is performed with tension band wiring, trans-osseous sutures, blade plates, semi-tubular plates, T-shape, buttress, and cloverleaf plates. The advent of locking plates has shifted the paradigm of internal fixation in PHF (Fig. 1). They are anatomically shaped to accommodate proximal humerus profile and their construct remains in a fixed angle irrespective of screw purchase and bone quality [45]: it relies on engagement of the screw on the plate, evenly distributing the load throughout the plate. This mechanism is particularly advantageous in osteoporotic

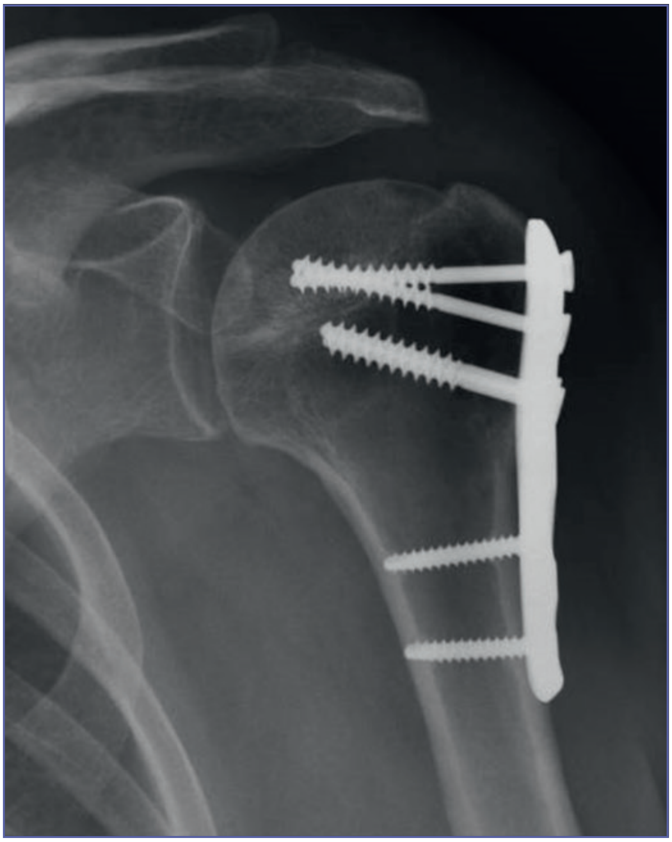

Figure 1. Osteosynthesis with locking plate for proximal humerus fracture.

bone. The conical pattern of proximal screw distribution supports the articular surface: screws act as pillars for subchondral bone [46].

To obtain good results in plating, the first mandatory step is fracture reduction. Anatomically reduced fractures warrant good clinical outcomes [47], while a malreduction of greater tuberosity of just 5 mm is associated with a threefold increase in complications, revisions, and risk of unsatisfactory clinical outcomes [47]. To ease tuberosity reduction, suture augmentation can be used. Sutures are passed through the tendinous insertion and fixed to the plate, relieving muscle stress from the fractured bone. Despite studies failing to demonstrate the biomechanical advantages of this technique [48,49], it may prove practically useful as a reduction aid. Plate positioning is another important issue. If the plate is placed too proximal, there is a high risk of impingement against the acromion. This can happen because of poor surgical technique, poor fracture reduction, or small proximal humerus size [37]. Altogether, plate positioning influences screw positioning and purchase, as locking screws have a fixed trajectory from the plate. Specifically, if the plate are too high, the calcar screw can be mispositioned, reducing construct stability [37].

Significant design differences exists among plates of different manufacturers [50], but similar clinical results can be obtained with different designs [51,52]. In a large meta-analysis [53] of patients undergoing internal fixation with locking plate, the average Constant score was 73.6, with better results with two-part fractures and worse results in four-part fractures, DASH score was 26.6, active forward flexion was 98° and average active abduction was 103°. Better results can be obtained in young patients after high energy traumas [54], even in head splitting fractures [55].

Medial support

Lack of medial support has been shown to cause reduction loss and varus deformity, leading to implant failure and postoperative osteonecrosis [56,57]. Various techniques have been proposed to deal with lack of medial support: use of a calcar screw, use of a strut allograft, cement augmentation, and dual plate fixation.

Calcar screw

The so-called calcar screw is a locking screw inserted through the plate, passing over the inferolateral wall of the great tuberosity, oblique to the medial cortex, directed towards the calcar region, providing additional support to the humeral head [58]. Ideally, it should be positioned < 12 mm from the apex of the arch of the calcar or within the bottom 25% of the humeral head [59], in the inferomedial quadrant of the humeral head [60]. Calcar screw malpositioning has been reported to occur in 24% of implants [61]. The main predictor of calcar screw malpositioning is the neck-shaft angle [61]. Reducing the head so that the neck-shaft angle fits the 130-150° range significantly reduces the risk of calcar screw malpositioning [61]. The use of a calcar screw provides a six-fold decrease in reoperation due to fixation failure [62]. In biomechanical testing of absence of medial cortex, it improved axial and shear stiffness [58]. Furthermore, it provided increased resistance to cyclic loading thanks to a stiffer bone implant structure [58]. Under the same biomechanical hypothesis, as a substitute of the calcar screw, a blade device has been proposed [63].

Void filling

This is a common finding after PHF reduction in which metaphyseal bone appears void. This can be due to slight malreduction, leaving some gaps, or cortical comminution or, hopefully, to cancellous bone impaction [64]. A possible solution is filling the defect with calcium phosphate. This decreases postoperative complications and reduces humeral head collapse compared to no augmentation and augmentation with cancellous chips [64]. Biomechanically, filling the humeral head void with calcium phosphate increases load to failure and stiffness, decreasing interfragmentary motion [65,66].

Strut graft

The use of a bone strut graft was first introduced by Gardner et al. [67] as a means to restore medial support in fractures with comminuted medial column. Fibular allograft has been considered the best choice to obtain medial augmentation: it fills the bone void of the humeral head, having a wide enough diameter to fill the entire proximal metaphysis; provides medial support and stability, preventing varus collapse of the humeral head; provides medial support for the greater tuberosity, allowing an anatomical reduction and restoring the rotator cuff length and function; provides endosteal purchase for locking screws, diminishing the torque placed on screws in case of varus or valgus stress; will not disturb the blood supply to the humeral head, providing altogether stable and osteogenic intramedullary material, fastening fracture healing [57,68]. With the use of a strut graft, biomechanical studies demonstrated an increase in construct stiffness and failure load, reduced fragment motion and change in gap distance [69-71], ultimately protecting from loss of reduction for varus collapse [72]. Good results in fractures with medial support loss have been obtained with this technique, with low loss of reduction [67,68,73,74] and better results compared to non-augmented constructs [68,74].

Dual plating

In complex PHF with medial cortex disruption, simple locking plates with calcar screw may be unable to grant mechanical stability. Double plating has been proposed as an alternative.

Wanner et al. [75] first described the use of an anterior and lateral plate. They reported encouraging clinical and radiographic results, with 12% of reoperations. Good clinical results were afterwards confirmed in a small series [76]. A biomechanical study did not demonstrate superiority of double plating over locking plate fixation with calcar screw [77]. Choi and colleagues [78] proposed adding a posteriorly placed distal radius locking plate to the standard lateral locking plate. Clinical outcomes of this technique have not yet been published. A finite element analysis [79] explored the effect on fracture stability of the addition of a medial plate. This construct demonstrated greater stiffness on axial loads and better restoration of neck-shaft angle compared with standard locking plate, strut graft, and locking plate combined with posterior plate. No clinical data have been provided however.

Bone cement augmentation

Augmentation of screw tips with PMMA increases resistance to failure in varus bending and axial rotation. This effect is markedly exerted on augmented screws purchasing the lowest density bone, and particularly evident in medially unstable fractures [80,81]. From a clinical standpoint, cement augmentation reduced the secondary displacement rate and provided satisfactory fracture healing; a drawback of this technique is in its most common complication: intra-articular cement leakage secondary to screw perforation [82].

CF-PEEK Plates

Metal plates are actually the most commonly used kind of implant. Their outcomes have been thoroughly evaluated and long follow-up is available. Recently, the use of carbon fiber-reinforced polyether ether ketone (CF-PEEK) plates has been proposed (Fig. 2).

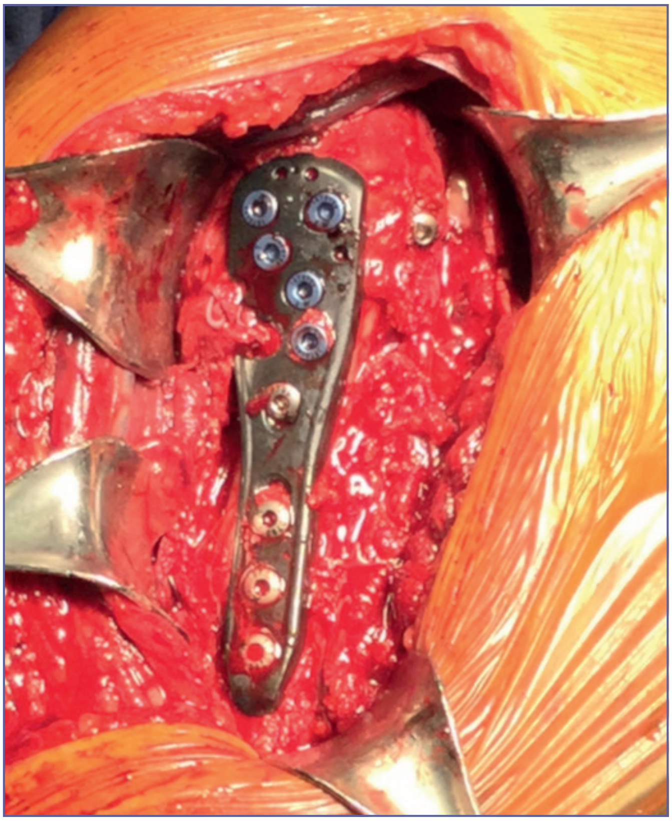

Figure 2. Osteosynthesis with a CF-PEEK locking plate.

CF-PEEK is a composite biomaterial composed of carbon fiber sheets embedded in a PEEK matrix. It is chemically inert and insoluble in conventional solvents at room temperature. CF-PEEK plates have many positive characteristics: unique mechanic properties, radiolucency, peculiar plate/screw interaction, and decreased risk of allergic reactions in metal-sensitive patients [83].

Elastic modulus of CF-PEEK is similar to that of cortical bone, conferring both high load-carrying capacity and low rigidity [84-86]. CF-PEEK plates demonstrated similar mechanical properties to that of titanium plates, except for bending strength, inferior by 20% to that of a metal proximal humerus plate, and yet adequate for proximal humerus fixation, with the advantage of decreased debris particles formation [84,85]. Its increased flexibility may exert a positive effect on fracture healing [87]; its elastic modulus should unload the screw-tip/bone interface and therefore lower the rate of secondary screw perforation and loss of reduction [88]. The radiolucency grants an easier intraoperative fluoroscopic evaluation of fracture reduction and greater tuberosity position and a clearer post-operative radiographic assessment of reduction loss and fracture healing (Fig. 3). Furthermore, it reduces the "starburst effect" and artifacts on CT and MRI, an advantageous characteristic for post-operative assessment and in the event of future pathologies [83,89]. Due to the difference in material composition, cold welding between plate and screws is avoided, allowing easier and safer hardware removal [83]. Locking screws of CF-PEEK plates can cut-through plate material, tapping their thread, or can lock to pre-machined threads in the plate holes [87]. No changes in biomechanical properties of the plate was detected depending on plate/screw interface [86]. CFR-PEEK plates show greater load to failure in the interface between distal locking screws and plate, with comparable stiffness with stainless steel plates.

In a multicenter study of 160 cases, at 2-year follow-up, good subjective and objective results were obtained; 5% of screw cut-out was observed, and 1.2% of backing out of screws from the plate. Two cases of non-union were registered and 8.1% of osteonecrosis. No foreign body reaction in tissues surrounding the implant was demonstrated [83]. Similar good clinical results were reported in other smaller series [88,90,91].

A comparison of CF-PEEK and historical cohorts of conventional plates demonstrated better clinical results of CF-PEEK plates over metal plates [90], but not confirmed by other authors [88]. Only one study directly compared the two types of implants: no clinical difference was observed, but greater bone remodelling under the plate was observed in CF-PEEK and higher tuberosity resorption in the metal group [91].

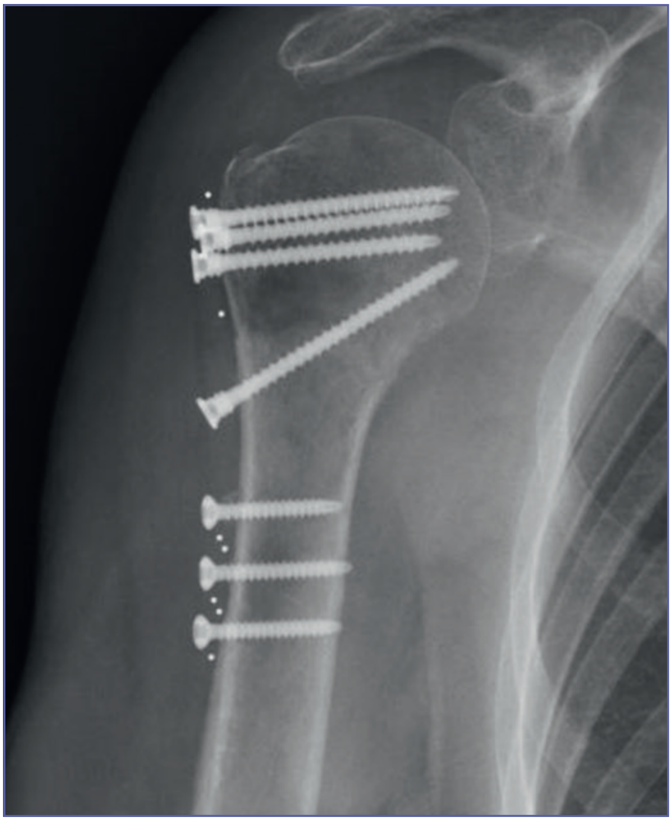

Figure 3. Post-operative imaging after osteosynthesis with a CF-PEEK plate.

Complications

A recent meta-analysis reported the complications of PHF treated with a locking plate. The most common complication was intraarticular screw penetration, found in 9.5% of cases, followed by varus collapse in 6.8%, subacromial impingement in 5.0%, avascular necrosis in 4.6%, adhesive capsulitis in 4.0%, non-union in 1.5%, and deep infection in 1.4% [92]. The cumulative reoperation rate was 13.8% [92]. Mechanical complications related to failure of the fixation; factors that were proved to be associated with fixation failure and, thus, predisposing to complications, are: low bone mineral density, quality of reduction (reduction of angulation, correction of head-shaft displacement and restoration of medial cortical support), age, screw length in the proximal rows of the plate, number of screws in the inferior part of the humeral head, and distance between screws and the articular surface [43,47,59,62,93].

Intra-articular screw penetration

Intra-articular screw penetration is the most common complication, leading to repeated surgery to remove the screws or even to revise the implant. It can be divided into primary penetration, when intraoperative screw malpositioning occurs, and secondary penetration, when screw penetration occurs after collapse of the humeral head. The majority of screw penetration occurs after avascular necrosis, in displaced articular fractures [94]. To reduce the incidence of this complication, placing screws at least 2-3 mm from the subchondral bone could be helpful [28].

Varus collapse

Varus collapse is one of the main complications of proximal humerus plating, as it will cause, in turn, screw penetration and subacromial impingement (Fig. 4). Restoration of medial hinge is mandatory to prevent varus collapse: a neck shaft angle reduction typically occurs during the first three months after surgery, with a mean loss of 3.8-4.9° [95,96], leading, in predisposed cases, to varus collapse. Factors associated with varus collapse are: presence of proximal screw cross-threading, initial calcar disruption, and a lack of reduction of calcar support [97].

Subacromial impingement

Subacromial impingement can be caused by positioning the lateral plate too high, malunion of the great tuberosity, or varus collapse of the humeral head. The most common cause is plate malpositioning, thus requiring hardware removal.

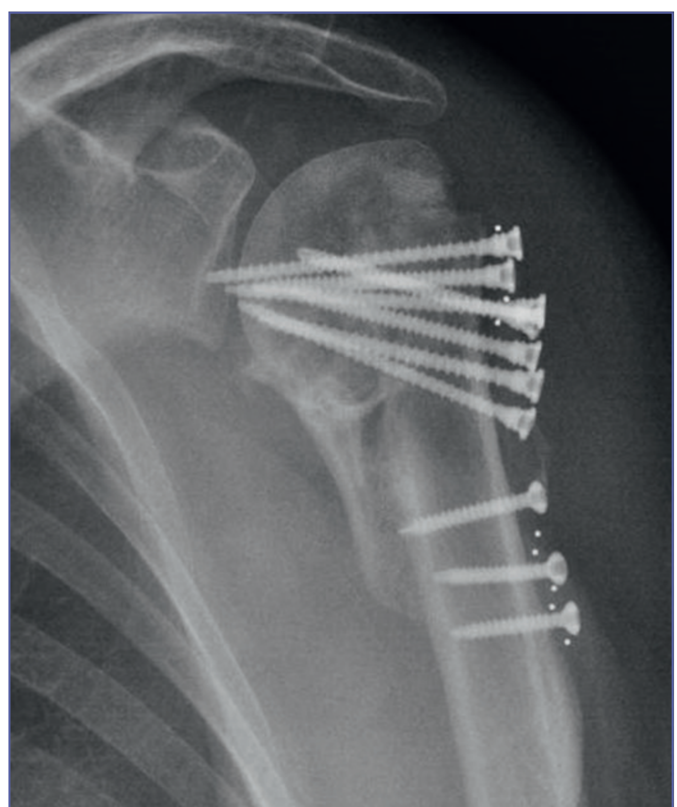

Figure 4. Varus collapse of the humeral head and intra-articular screw penetration.

Avascular necrosis

Osteonecrosis is a delayed complication, being diagnosed at a mean 11.8 months after surgery [98] and, not surprisingly, leading to worse clinical outcomes [98]. Among predictors of osteonecrosis, varus collapse of the humeral head, disrupted medial calcar, poor reduction, diabetes mellitus, chronic kidney disease, and chronic liver disease were found [56,99]. Development of avascular necrosis depends on a combination of mechanical and biological aspects. Impairment of humeral head vascularization is a common event after a PHF, as vessels are commonly involved. Humeral head ischemia is the first step towards osteonecrosis. Hertel et al. [9] evaluated factors associated with humeral head ischemia. These were: short calcar, disrupted medial hinge and anatomic neck fracture [9]. Posteromedial extension of the humeral head fragment is inversely correlated to humeral head ischemia: the shorter the calcar fragment, the less perfused the head was [9]. Hertel's criteria were demonstrated to be predictive of osteonecrosis [99]. Despite this, even in an ischemic head, revascularization or creepy substitution can happen: only 20% of instrumentally proven ischemic heads suffered, after 2 years, of avascular necrosis [100].

Conclusions

Locking plate osteosynthesis is widely considered the main option for surgical treatment of PHF. It can provide excellent clinical results, but high complication rates have been reported. Indications for plate fixation are elusive: careful selection of patients based on surgeon's knowledge and experience is mandatory to avoid unwanted complications. Various augments and plate designs have been proposed, yet none demonstrated clear superiority over the others. Further research, improved techniques, and implant refinements are still needed to clarify the indications and provide uniform results to patients.

References

1. Passaretti D, Candela V, Sessa P, et al. Epidemiology of proximal humeral fractures: a detailed survey of 711 patients in a metropolitan area. J Shoulder Elbow Surg 2017;26:2117-2124. https://doi.org/10.1016/j.jse.2017.05.029
2. Launonen AP, Lepola V, Saranko A, et al. Epidemiology of proximal humerus fractures. Arch Osteoporos 2015;10:2. https://doi.org/10.1007/s11657-015-0209-4
3. Court-Brown CM, Caesar B. Epidemiology of adult fractures: A review. Injury 2006;37:691-697. https://doi.org/10.1016/j.injury.2006.04.130
4. Palvanen M, Kannus P, Niemi S, et al. Update in the epidemiology of proximal humeral fractures. Clin Orthop Relat Res 2006;442:87-92. https://doi.org/10.1097/01.blo.0000194672.79634.78
5. Bergdahl C, Wennergren D, Ekelund J, et al. Mortality after a proximal humeral fracture. Bone Joint J 2020;102-B:1484-1490. https://doi.org/10.1302/0301-620X.102B11.BJJ-2020-0627.R1
6. Feissli S, Audigé L, Steinitz A, et al. Treatment options for proximal humeral fractures in the older adults and their implication on personal independence. Arch Orthop Trauma Surg 2020;140:1971-1976. https://doi.org/10.1007/s00402-020-03452-0
7. Maravic M, Briot K, Roux C. Burden of proximal humerus fractures in the French National Hospital Database. Orthop Traumatol Surg Res 2014;100:931-934. https://doi.org/10.1016/j.otsr.2014.09.017
8. Neer CS. Displaced proximal humeral fractures. I. Classification and evaluation. J Bone Joint Surg Am 1970;52:1077-1089.
9. Hertel R, Hempfing A, Stiehler M, et al. Predictors of humeral head ischemia after intracapsular fracture of the proximal humerus. J Shoulder Elbow Surg 2004;13:427-433. https://doi.org/10.1016/j.jse.2004.01.034
10. Meinberg EG, Agel J, Roberts CS, et al. Fracture and dislocation Classification Compendium-2018. J Orthop Trauma 2018;32(Suppl 1):S1-S170. https://doi.org/10.1097/BOT.0000000000001063
11. Nowak LL, Vicente MR, McKee MD, et al. Orthopaedic surgeons' opinions surrounding the management of proximal humerus fractures: an international survey. Int Orthop 2017;41:1749-1755. https://doi.org/10.1007/s00264-017-3569-0
12. Codman EA. Fractures in relation to the subacromial bursa. In: The shoulder, rupture of the supraspinatus tendon and other lesions in or about the subacromial Bursa. Malabar, FL: Krieger Publishing 1934, pp. 313-331.
13. Neer CS. Four-segment classification of proximal humeral fractures: purpose and reliable use. J Shoulder Elbow Surg 2002;11:389-400. https://doi.org/10.1067/mse.2002.124346
14. Brorson S, Olsen BS, Frich LH, et al. Surgeons agree more on treatment recommendations than on classification of proximal humeral fractures. BMC Musculoskelet Disord 2012;13:114. https://doi.org/10.1186/1471-2474-13-114
15. Papakonstantinou MK, Hart MJ, Farrugia R, et al. Interobserver agreement of Neer and AO classifications for proximal humeral fractures. ANZ J Surg 2016;86:280-284. https://doi.org/10.1111/ans.13451
16. Sjödén GO, Movin T, Güntner P, et al. Poor reproducibility of classification of proximal humeral fractures. Additional CT of minor value. Acta Orthop Scand 1997;68:239-242. https://doi.org/10.3109/17453679708996692
17. Majed A, Macleod I, Bull AMJ, et al. Proximal humeral fracture classification systems revisited. J Shoulder Elbow Surg 2011;20:1125-1132. https://doi.org/10.1016/j.jse.2011.01.020
18. Bernstein J, Adler LM, Blank JE, et al. Evaluation of the Neer system of classification of proximal humeral fractures with computerized tomographic scans and plain radiographs. J Bone Joint Surg Am 1996;78:1371-1375. https://doi.org/10.2106/00004623-199609000-00012
19. Siebenrock KA, Gerber C. The reproducibility of classification of fractures of the proximal end of the humerus. J Bone Joint Surg Am 1993;75:1751-1755. https://doi.org/10.2106/00004623-199312000-00003
20. Iordens GIT, Mahabier KC, Buisman FE, et al. The reliability and reproducibility of the Hertel classification for comminuted proximal humeral fractures compared with the Neer classification. J Orthop Sci 2016;21:596-602. https://doi.org/10.1016/j.jos.2016.05.011
21. Stoddart M, Pearce O, Smith J, et al. Proximal humerus fractures: reliability of neer versus AO Classification on plain radiographs and computed tomography. Cureus 2020;12:e8520. https://doi.org/10.7759/cureus.8520

[22] LaMartina J, Christmas KN, Simon P, et al. Difficulty in decision making in the treatment of displaced proximal humerus fractures: the effect of uncertainty on surgical outcomes. J Shoulder Elbow Surg 2018;27:470-477. https://doi.org/10.1016/j.jse.2017.09.033

[23] Brorson S, Eckardt H, Audigé L, et al. Translation between the Neer- and the AO/OTA-classification for proximal humeral fractures: do we need to be bilingual to interpret the scientific literature? BMC Res Notes 2013;6:69. https://doi.org/10.1186/1756-0500-6-69

[24] Tejwani NC, Liporace F, Walsh M, et al. Functional outcome following one-part proximal humeral fractures: a prospective study. J Shoulder Elbow Surg 2008;17:216-219. https://doi.org/10.1016/j.jse.2007.07.016

[25] Bell J-E, Leung BC, Spratt KF, et al. Trends and variation in incidence, surgical treatment, and repeat surgery of proximal humeral fractures in the elderly. J Bone Joint Surg Am 2011;93:121-131. https://doi.org/10.2106/JBJS.I.01505

[26] Launonen AP, Lepola V, Laitinen M, et al. Do treatment policies for proximal humerus fractures differ among three Nordic countries and Estonia? Results of a survey study. Scand J Surg 2016;105:186-190. https://doi.org/10.1177/1457496915623149

[27] Rangan A, Handoll H, Brealey S, et al. Surgical vs nonsurgical treatment of adults with displaced fractures of the proximal humerus: the PROFHER randomized clinical trial. JAMA 2015;313:1037-1047. https://doi.org/10.1001/jama.2015.1629

[28] Olerud P, Ahrengart L, Ponzer S, et al. Internal fixation versus nonoperative treatment of displaced 3-part proximal humeral fractures in elderly patients: a randomized controlled trial. J Shoulder Elbow Surg 2011;20:747-755. https://doi.org/10.1016/j.jse.2010.12.018

[29] Bosch U, Skutek M, Fremerey RW, et al. Outcome after primary and secondary hemiarthroplasty in elderly patients with fractures of the proximal humerus. J Shoulder Elbow Surg 1998;7:479-484. https://doi.org/10.1016/s1058-2746(98)90198-7

[30] Handoll HH, Keding A, Corbacho B, et al. Five-year follow-up results of the PROFHER trial comparing operative and non-operative treatment of adults with a displaced fracture of the proximal humerus. Bone Joint J 2017;99-B:383-392. https://doi.org/10.1302/0301-620X.99B3.BJJ-2016-1028

[31] Corbacho B, Duarte A, Keding A, et al. Cost effectiveness of surgical versus non-surgical treatment of adults with displaced fractures of the proximal humerus: economic evaluation alongside the PROFHER trial. Bone Joint J 2016;98-B:152-159. https://doi.org/10.1302/0301-620X.98B2.36614

[32] Launonen AP, Sumrein BO, Reito A, et al. Operative versus non-operative treatment for 2-part proximal humerus fracture: a multicenter randomized controlled trial. PLoS Med 2019;16:e1002855. https://doi.org/10.1371/journal.pmed.1002855

[33] Barlow JD, Logli AL, Steinmann SP, et al. Locking plate fixation of proximal humerus fractures in patients older than 60 years continues to be associated with a high complication rate. J Shoulder Elbow Surg 2020;29:1689-1694. https://doi.org/10.1016/j.jse.2019.11.026

[34] Beks RB, Ochen Y, Frima H, et al. Operative versus nonoperative treatment of proximal humeral fractures: a systematic review, meta-analysis, and comparison of observational studies and randomized controlled trials. J Shoulder Elbow Surg 2018;27:1526-1534. https://doi.org/10.1016/j.jse.2018.03.009

[35] Jefferson L, Brealey S, Handoll H, et al. Impact of the PROFHER trial findings on surgeons' clinical practice: an online questionnaire survey. Bone Joint Res 2017;6:590-599. https://doi.org/10.1302/2046-3758.610.BJR-2017-0170

[36] Steinhaus ME, Dare DM, Gulotta LV. Displaced proximal humerus fractures: is a sling as good as a plate? HSS J 2016;12:287-290. https://doi.org/10.1007/s11420-015-9479-z

[37] Stone MA, Namdari S. Surgical considerations in the treatment of osteoporotic proximal humerus fractures. Orthop Clin North Am 2019;50:223-231. https://doi.org/10.1016/j.ocl.2018.10.005

[38] Goch AM, Christiano A, Konda SR, et al. Operative repair of proximal humerus fractures in septuagenarians and octogenarians: does chronologic age matter? J Clin Orthop Trauma 2017;8:50-53. https://doi.org/10.1016/j.jcot.2017.01.006

[39] Grawe B, Le T, Lee T, et al. Open Reduction and Internal Fixation (ORIF) of complex 3- and 4-part fractures of the proximal humerus: does age really matter? Geriatr Orthop Surg Rehabil 2012;3:27-32. https://doi.org/10.1177/2151458511430662

[40] Lollino N, Paladini P, Campi F, et al. Reverse shoulder prosthesis as revision surgery after fractures of the proximal humerus, treated initially by internal fixation or hemiarthroplasty. Chir Organi Mov 2009;93(Suppl 1):S35-39. https://doi.org/10.1007/s12306-009-0006-6

[41] Laux CJ, Grubhofer F, Werner CML, et al. Current concepts in locking plate fixation of proximal humerus fractures. J Orthop Surg 2017;12:137. https://doi.org/10.1186/s13018-017-0639-3

[42] Wendt KW, Jaeger M, Verbruggen J, et al. ESTES recommendations on proximal humerus fractures in the elderly. Eur J Trauma Emerg Surg 2020;Aug 20. https://doi.org/10.1007/s00068-020-01437-7 [Epub Ahead of Print]

[43] Spross C, Zeledon R, Zdravkovic V, et al. How bone quality may influence intraoperative and early postoperative problems after angular stable open reduction-internal fixation of proximal humeral fractures. J Shoulder Elbow Surg 2017;26:1566-1572. https://doi.org/10.1016/j.jse.2017.02.026

[44] Carbone S, Papalia M. The amount of impaction and loss of reduction in osteoporotic proximal humeral fractures after surgical fixation. Osteoporos Int 2016;27:627-633. https://doi.org/10.1007/s00198-015-3304-x

[45] Seide K, Triebe J, Faschingbauer M, et al. Locked vs unlocked plate osteosynthesis of the proximal humerus – a biomechanical study. Clin Biomech 2007;22:176-182. https://doi.org/10.1016/j.clinbiomech.2006.08.009

[46] Chen J-L, Chang F-C, Lin S-J, et al. The outcome of surgical management of proximal humeral fractures using locking plates: comparison between locking plates with different geometry. J Shoulder Elbow Surg 2018;27:2159-2166. https://doi.org/10.1016/j.jse.2018.05.033

[47] Schnetzke M, Bockmeyer J, Porschke F, et al. Quality of reduction influences outcome after locked-plate fixation of proximal humeral type-C fractures. J Bone Joint Surg Am 2016;98:1777-1785. https://doi.org/10.2106/JBJS.16.00112

[48] Voigt C, Hurschler C, Rechi L, et al. Additive fiber-cerclages in proximal humeral fractures stabilized by locking plates: no effect on fracture stabilization and rotator cuff function in human shoulder specimens. Acta Orthop 2009;80:465-471. https://doi.org/10.3109/17453670903110659

[49] Arvesen JE, Gill SW, Sinatra PM, et al. Biomechanical contribution of tension-reducing rotator cuff sutures in 3-part proximal

humerus fractures. J Orthop Trauma 2016;30:e262-266. https://doi.org/10.1097/BOT.0000000000000575
50 McDonald E, Kwiat D, Kandemir U. Geometry of proximal humerus locking plates. J Orthop Trauma 2015;29:e425. https://doi.org/10.1097/BOT.0000000000000371
51 Gumina S, Baudi P, Candela V, et al. Hertel 7 fracture of the humeral head. Can two different fixation systems (Diphos/PHP) lead to different outcomes? A retrospective study. Injury 2016;47(Suppl 4):S59-S63. https://doi.org/10.1016/j.injury.2016.07.051
52 Konrad G, Hirschmüller A, Audige L, et al. Comparison of two different locking plates for two-, three- and four-part proximal humeral fractures – results of an international multicentre study. Int Orthop 2012;36:1051-1058. https://doi.org/10.1007/s00264-011-1410-8
53 Sproul RC, Iyengar JJ, Devcic Z, et al. A systematic review of locking plate fixation of proximal humerus fractures. Injury 2011;42:408-413. https://doi.org/10.1016/j.injury.2010.11.058
54 Mariadoss A, Thacker J, Krishnanunni K, et al. The outcome of proximal humeral locking plates in the management of three and four part proximal humeral fractures in special cohort of young patients in high velocity trauma. Arch Bone Jt Surg 2019;7:38-45.
55 Gavaskar AS, Tummala NC. Locked plate osteosynthesis of humeral head-splitting fractures in young adults. J Shoulder Elbow Surg 2015;24:908-914. https://doi.org/10.1016/j.jse.2014.10.003
56 Lin S-J, Tsai Y-H, Yang T-Y, et al. Medial calcar support and radiographic outcomes of plate fixation for proximal humeral fractures. BioMed Res Int 2015;2015:170283. https://doi.org/10.1155/2015/170283
57 Davids S, Allen D, Desarno M, et al. Comparison of locked plating of varus displaced proximal humeral fractures with and without fibula allograft augmentation. J Orthop Trauma 2020;34:186-192. https://doi.org/10.1097/BOT.0000000000001679
58 Bai L, Fu Z, An S, et al. Effect of calcar screw use in surgical neck fractures of the proximal humerus with unstable medial support: a biomechanical study. J Orthop Trauma 2014;28:452-457. https://doi.org/10.1097/BOT.0000000000000057
59 Padegimas EM, Zmistowski B, Lawrence C, et al. Defining optimal calcar screw positioning in proximal humerus fracture fixation. J Shoulder Elbow Surg 2017;26:1931-1937. https://doi.org/10.1016/j.jse.2017.05.003
60 Mehta S, Chin M, Sanville J, et al. Calcar screw position in proximal humerus fracture fixation: don't miss high! Injury 2018;49:624-629. https://doi.org/10.1016/j.injury.2018.02.007
61 Wang Q, Sheng N, Rui B, et al. The neck-shaft angle is the key factor for the positioning of calcar screw when treating proximal humeral fractures with a locking plate. Bone Joint J 2020;102-B:1629-1635. https://doi.org/10.1302/0301-620X.102B12.BJJ-2020-0070.R1
62 Oppebøen S, Wikerøy AKB, Fuglesang HFS, et al. Calcar screws and adequate reduction reduced the risk of fixation failure in proximal humeral fractures treated with a locking plate: 190 patients followed for a mean of 3 years. J Orthop Surg 2018;13:197. https://doi.org/10.1186/s13018-018-0906-y
63 Beirer M, Crönlein M, Venjakob AJ, et al. Additional calcar support using a blade device reduces secondary varus displacement following reconstruction of the proximal humerus: a prospective study. Eur J Med Res 2015;20:82. https://doi.org/10.1186/s40001-015-0178-5
64 Egol KA, Sugi MT, Ong CC, et al. Fracture site augmentation with calcium phosphate cement reduces screw penetration after open reduction-internal fixation of proximal humeral fractures. J Shoulder Elbow Surg 2012;21:741-748. https://doi.org/10.1016/j.jse.2011.09.017
65 Kennedy J, Molony D, Burke NG, et al. Effect of calcium triphosphate cement on proximal humeral fracture osteosynthesis: a cadaveric biomechanical study. J Orthop Surg (Hong Kong) 2013;21:173-177. https://doi.org/10.1177/230949901302100211
66 Gradl G, Knobe M, Stoffel M, et al. Biomechanical evaluation of locking plate fixation of proximal humeral fractures augmented with calcium phosphate cement. J Orthop Trauma 2013;27:399-404. https://doi.org/10.1097/BOT.0b013e318278c595
67 Gardner MJ, Boraiah S, Helfet DL, et al. Indirect medial reduction and strut support of proximal humerus fractures using an endosteal implant. J Orthop Trauma 2008;22:195-200. https://doi.org/10.1097/BOT.0b013e31815b3922
68 Chen H, Yin P, Wang S, et al. The augment of the stability in locking compression plate with intramedullary fibular allograft for proximal humerus fractures in elderly people. BioMed Res Int 2018;2018:3130625. https://doi.org/10.1155/2018/3130625
69 Bae J-H, Oh J-K, Chon C-S, et al. The biomechanical performance of locking plate fixation with intramedullary fibular strut graft augmentation in the treatment of unstable fractures of the proximal humerus. J Bone Joint Surg Br 2011;93:937-941. https://doi.org/10.1302/0301-620X.93B7.26125
70 Mathison C, Chaudhary R, Beaupre L, et al. Biomechanical analysis of proximal humeral fixation using locking plate fixation with an intramedullary fibular allograft. Clin Biomech 2010;25:642-646. https://doi.org/10.1016/j.clinbiomech.2010.04.006
71 Osterhoff G, Baumgartner D, Favre P, et al. Medial support by fibula bone graft in angular stable plate fixation of proximal humeral fractures: an in vitro study with synthetic bone. J Shoulder Elbow Surg 2011;20:740-746. https://doi.org/10.1016/j.jse.2010.10.040
72 Chow RM, Begum F, Beaupre LA, et al. Proximal humeral fracture fixation: locking plate construct ± intramedullary fibular allograft. J Shoulder Elbow Surg 2012;21:894-901. https://doi.org/10.1016/j.jse.2011.04.015
73 Wang H, Rui B, Lu S, et al. Locking plate use with or without strut support for varus displaced proximal humeral fractures in elderly patients. JB JS Open Access 2019;4:e0060.1-8. https://doi.org/10.2106/JBJS.OA.18.00060
74 Zhang L, Zheng J, Wang W, et al. The clinical benefit of medial support screws in locking plating of proximal humerus fractures: a prospective randomized study. Int Orthop 2011;35:1655-1661. https://doi.org/10.1007/s00264-011-1227-5
75 Wanner GA, Wanner-Schmid E, Romero J, et al. Internal fixation of displaced proximal humeral fractures with two one-third tubular plates. J Trauma 2003;54:536-544. https://doi.org/10.1097/01.TA.0000052365.96538.42
76 Theopold J, Marquaß B, Fakler J, et al. The bicipital groove as a landmark for reconstruction of complex proximal humeral fractures with hybrid double plate osteosynthesis. BMC Surg 2016;16:10. https://doi.org/10.1186/s12893-016-0125-6
77 Theopold J, Schleifenbaum S, Müller M, et al. Biomechanical evaluation of hybrid double plate osteosynthesis using a locking plate and an inverted third tubular plate for the treatment of proximal humeral fractures. PLoS One 2018;13:e0206349. https://doi.org/10.1371/journal.pone.0206349

[78] Choi S, Kang H, Bang H. Technical tips: dualplate fixation technique for comminuted proximal humerus fractures. Injury 2014;45:1280-1282. https://doi.org/10.1016/j.injury.2014.04.029

[79] He Y, Zhang Y, Wang Y, et al. Biomechanical evaluation of a novel dualplate fixation method for proximal humeral fractures without medial support. J Orthop Surg 2017;12:72. https://doi.org/10.1186/s13018-017-0573-4

[80] Unger S, Erhart S, Kralinger F, et al. The effect of in situ augmentation on implant anchorage in proximal humeral head fractures. Injury 2012;43:1759-1763. https://doi.org/10.1016/j.injury.2012.07.003

[81] Kathrein S, Kralinger F, Blauth M, et al. Biomechanical comparison of an angular stable plate with augmented and non-augmented screws in a newly developed shoulder test bench. Clin Biomech 2013;28:273-277. https://doi.org/10.1016/j.clinbiomech.2012.12.013

[82] Knierzinger D, Crepaz-Eger U, Hengg C, et al. Does cement augmentation of the screws in angular stable plating for proximal humerus fractures influence the radiological outcome: a retrospective assessment. Arch Orthop Trauma Surg 2020;140:1413-1421. https://doi.org/10.1007/s00402-020-03362-1

[83] Rotini R, Cavaciocchi M, Fabbri D, et al. Proximal humeral fracture fixation: multicenter study with carbon fiber peek plate. Musculoskelet Surg 2015;99(Suppl 1):S1-8. https://doi.org/10.1007/s12306-015-0371-2

[84] Steinberg EL, Rath E, Shlaifer A, et al. Carbon fiber reinforced PEEK Optima – a composite material biomechanical properties and wear/debris characteristics of CF-PEEK composites for orthopedic trauma implants. J Mech Behav Biomed Mater 2013;17:221-228. https://doi.org/10.1016/j.jmbbm.2012.09.013

[85] Feerick EM, Kennedy J, Mullett H, et al. Investigation of metallic and carbon fibre PEEK fracture fixation devices for three-part proximal humeral fractures. Med Eng Phys 2013;35:712-722. doi:10.1016/j.medengphy.2012.07.016

[86] Katthagen JC, Schwarze M, Warnhoff M, et al. Influence of plate material and screw design on stiffness and ultimate load of locked plating in osteoporotic proximal humeral fractures. Injury 2016;47:617-624. https://doi.org/10.1016/j.injury.2016.01.004

[87] Hak DJ, Fader R, Baldini T, et al. Locking screw-plate interface stability in carbon-fibre reinforced polyetheretherketone proximal humerus plates. Int Orthop 2017;41:1735-1739. https://doi.org/10.1007/s00264-017-3562-7

[88] Katthagen JC, Ellwein A, Lutz O, et al. Outcomes of proximal humeral fracture fixation with locked CFR-PEEK plating. Eur J Orthop Surg Traumatol Orthop Traumatol 2017;27:351-358. https://doi.org/10.1007/s00590-016-1891-7

[89] Hak DJ, Mauffrey C, Seligson D, et al. Use of carbon-fiber-reinforced composite implants in orthopedic surgery. Orthopedics 2014;37:825-830. https://doi.org/10.3928/01477447-20141124-05

[90] Schliemann B, Seifert R, Theisen C, et al. PEEK versus titanium locking plates for proximal humerus fracture fixation: a comparative biomechanical study in two- and three-part fractures. Arch Orthop Trauma Surg 2017;137:63-71. https://doi.org/10.1007/s00402-016-2620-8

[91] Padolino A, Porcellini G, Guollo B, et al. Comparison of CFR-PEEK and conventional titanium locking plates for proximal humeral fractures: a retrospective controlled study of patient outcomes. Musculoskelet Surg 2018;102(Suppl 1):49-56. https://doi.org/10.1007/s12306-018-0562-8

[92] Kavuri V, Bowden B, Kumar N, et al. Complications associated with locking plate of proximal humerus fractures. Indian J Orthop 2018;52:108-116. https://doi.org/10.4103/ortho.IJOrtho_243_17

[93] Laflamme G-Y, Moisan P, Chapleau J, et al. Novel technical factors affecting proximal humerus fixation stability. J Orthop Trauma 2020;Oct 30. https://doi.org/10.1097/BOT.0000000000001984 [Epub ahead of Print]

[94] Fjalestad T, Hole MØ, Hovden IAH, et al. Surgical treatment with an angular stable plate for complex displaced proximal humeral fractures in elderly patients: a randomized controlled trial. J Orthop Trauma 2012;26:98-106. https://doi.org/10.1097/BOT.0b013e31821c2e15

[95] Wang J-Q, Jiang B-J, Guo W-J, et al. Serial changes in the head-shaft angle of proximal humeral fractures treated by placing locking plates: a retrospective study. BMC Musculoskelet Disord 2018;19:420. https://doi.org/10.1186/s12891-018-2349-3

[96] Pawaskar AC, Lee K-W, Kim J-M, et al. Locking plate for proximal humeral fracture in the elderly population: serial change of neck shaft angle. Clin Orthop Surg 2012;4:209-215. https://doi.org/10.4055/cios.2012.4.3.209

[97] Padegimas EM, Chang G, Namjouyan K, et al. Failure to restore the calcar and locking screw cross-threading predicts varus collapse in proximal humerus fracture fixation. J Shoulder Elbow Surg 2020;29:291-295. https://doi.org/10.1016/j.jse.2019.06.014

[98] Belayneh R, Lott A, Haglin J, et al. Osteonecrosis after surgically repaired proximal humerus fractures is a predictor of poor outcomes. J Orthop Trauma 2018;32:e387-e393. https://doi.org/10.1097/BOT.0000000000001260

[99] Campochiaro G, Rebuzzi M, Baudi P, et al. Complex proximal humerus fractures: Hertel's criteria reliability to predict head necrosis. Musculoskelet Surg 2015;99(Suppl 1):S9-15. https://doi.org/10.1007/s12306-015-0358-z

[100] Bastian JD, Hertel R. Initial post-fracture humeral head ischemia does not predict development of necrosis. J Shoulder Elbow Surg 2008;17:2-8. https://doi.org/10.1016/j.jse.2007.03.026