The Current Status of Locked Plating: The Good, the Bad, and the Ugly

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Abstract: Locked plate technology has evolved in an effort to overcome the limitations associated with conventional plating methods, primarily for improving fixation in osteopenic bone. The development of screw torque and plate-bone interface friction is unnecessary with locked plate designs, significantly decreasing the amount of soft tissue dissection required for implantation, preserving the periosteal blood supply, and facilitating the use of minimally invasive percutaneous bridging fixation techniques. The locked plate is a fixed-angle device because angular motion does not occur at the plate screw interface. The use of locked plate technology allows the orthopaedic surgeon to manage fractures with indirect reduction techniques while providing stable fracture fixation. The secure 'feel' of locked plates, ease of application, and the low incidence of complications noted in early clinical reports have contributed to the proliferation of this technology. Along with reports of clinical successes, as the use of fixed angle/locked plates has increased, clinical failures are being noticed. This review will focus on the biomechanics of locked plate technology, appropriate indications for its use, laboratory and clinical comparisons to conventional plating techniques, and potential mechanisms of locked plate failure that have been observed.

Key Words: locked plate, failure, complications

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INTRODUCTION

For the past 50 years, the general principles of fracture fixation have been developed, tested, and promoted by the AO group.[1,2] The original principles included direct fracture exposure, precise reduction, and rigid internal fixation through compression in an effort to achieve an anatomic fracture union.[3,4] This conventional fracture management technique often required a significant surgical exposure, altering the biologic environment at and around the fracture site through soft tissue stripping and devascularization.[4,5] Consequences of iatrogenic soft tissue trauma, however, often resulted in the development of delayed fracture union, nonunion, and infection.

A refined understanding of bone biology and the roles tissue vascularity and gap strain play in fracture healing, contributed to the development of the concept of bridging plate osteosynthesis and the use of locked plate technology.[3,5] The success of bridging fixation spurred an interest in creation of an internal fixator. The Schuhli-Nut, Pc-Fix, and Zespol plates were early attempts at creating an internal fixator.[6,7] By firmly fixing the screw to the plate, the plate screw construct could act as a fixed-angle device, with the screws functioning as threaded locked bolts.[4,8,9] Similar to the bars of an external fixator, plates were not applied directly to the bone, thereby providing elastic fixation, which facilitated fracture union through secondary bone healing with callus formation.[3,5,9] Free of the need to apply the plates directly to the bony surface, the locked plate created a more biologic approach to the management of fractures, allowing for indirect reduction using minimally invasive percutaneous plating techniques.

The secure feel of locked plates, the relative ease of application, and the low incidence of complications reported in early clinical studies contributed to the proliferation of this technology for fracture fixation. Laboratory and clinical studies demonstrated that locked plate fixation for certain fracture types provided superior construct stability and improved outcomes.[4,10–17] As the use of fixed-angle/locked plates increased, reports of clinical failures came along with reports of clinical successes. As a result, the current paper reviews the biomechanics of locked plate technology, appropriate indications for its use, laboratory and clinical comparisons with conventional fixation techniques, and identifies the potential mechanisms of locked plate failure that have been observed.

Biomechanics of Locked Plate Technology

Fracture fixation with traditional compression plating techniques uses the frictional force created between the plate and bone to counteract the external forces experienced at the fracture site.[18] Stability with these traditional plate and screw constructs is primarily achieved via screw torque. Variables such as bone quality and fracture comminution affect the quality of screw thread purchase and the resultant fixation stability achieved with compression plating. By a variety of mechanisms, the screws in a locked plating system are designed to lock into the plate, eliminating screw toggle and creating a fixed-angle, single-beam construct.[3,8] When using locked plates in a bridging manner, the edges of the fracture are not compressed together at the fracture site as is commonplace with conventional plating techniques.[4] Instead, the locked plate acts as an internal-external fixator to bridge the fracture, providing relative stability while allowing enough

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strain at the fracture site to promote secondary healing with callus formation.[3,5,8,9]

Biomechanically, the locked plate system is designed to convert the shear forces experienced at the implant with the application of load into compressive forces at the screw-bone interface.[3,19] This force conversion is beneficial in fracture fixation because cortical bone is stronger against compressive loads than shear loads. Additionally, the angular stability of locked screws allows the applied load to be more evenly distributed amongst the component screws, avoiding significant load concentration at a single screw-bone interface.[3,4,20] This leads to the overall fixation strength of the locked plate system, equaling the sum of fixation strengths of all screw-bone interfaces instead of that of a single component screw as in conventional plating.[3,8,19,20]

Acting as an internal-external fixator, the fixation rigidity of the locked plate system benefits from the proximity of the plate to the bone and fracture site, with locked screw lengths being significantly shorter than conventional external fixator pins.[3] The overall stability provided by the locked plate system across the fracture site becomes dependent on the amount of load applied and the mechanical properties of the plate itself.[3,4] The extent of the elastic motion that occurs is dictated by the length of the plate, the cross-sectional area of the plate, the material properties of the plate, the density and diameter of the inserted screws, and the use of unicortical versus bicortical screws.[3,4,21] The choice of locked plate length is a key element in the fracture fixation stability provided by the construct and varies according to fracture pattern.[22] Recommendations regarding the length of the locked plate typically include using an implant that is 8 to 10 times the length of the fracture in simple patterns and 3 times the length in comminuted fracture patterns.[4,21,23,24] At least 2 screws per main fragment should be inserted, with 3 cortices of purchase for simple fractures and at least 2 screws and 4 cortices for comminuted fractures.[3,21,24,25] Additionally, a screw-to-hole ratio less than 0.5 limits the bending moments experienced at the most proximal and distal screws, and a span of 2 to 3 open screw holes should be left over the fracture site to help limit the concentration of stress at the adjacent screw-bone interfaces.[4,23,26,27]

Newer locked plate designs, including those using combination-hole technology, allow surgeons to incorporate aspects of locked plating and compression plating into 1 implant. In combining the two fixation methods, the surgeon potentially negates the theoretical advantages of each, creating an environment at the fracture site, where excessive gap strains lead to the development of nonunion.[3,5] An example of this (Figure 1) occurs when the ends of a simple fracture are brought within close proximity but are not compressed. In this situation, the stiffness of the plate and rigidity of the construct prevent bone contact, while the strains at the persistent fracture gap prohibit the formation of bone. This is complicated by the fact that the only way for the locked plate to dynamize is to undergo plastic deformation or break. Combination plates may be useful in certain fracture patterns in which one aspect of the fracture would benefit from anatomic reduction and compression (ie, intraarticular component or simple fracture patterns in pathological bone), whereas another fracture component would benefit from bridging fixation (ie, comminuted metadiaphyseal portion).[3,4] However, when these criteria are met, it is important to complete maximal fracture compression with lag screws before locked screws are inserted, and the plate should be placed on the tension side of the fracture to neutralize the forces acting on the interfragmentary compression screws.[3]

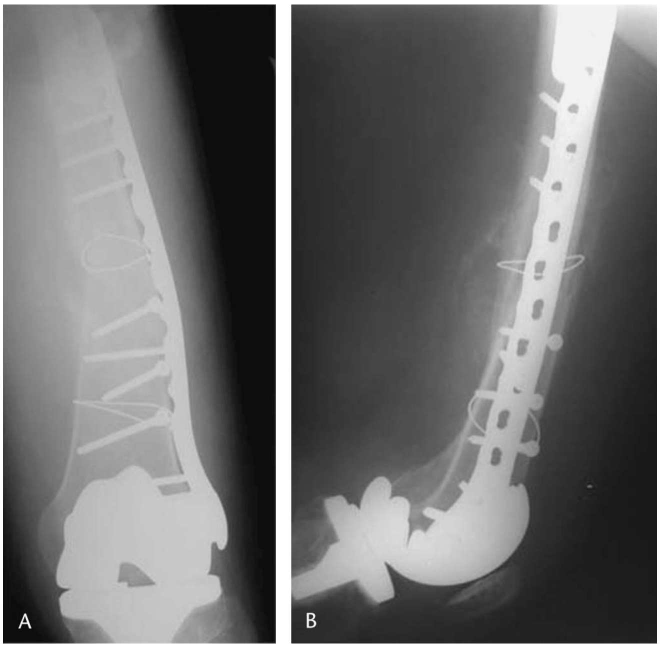

FIGURE 1. Example of plate bending that occurred in a 63-year-old mam who sustained a spiral periprosthetic left femur fracture 1 month after a total knee replacement. The fracture was managed with a 15-hole locked plate construct. As seen on the (A) anteroposterior and (B) lateral x-rays taken at the 3-week follow-up visit, repeated stresses concentrated over the fracture site exceeded the mechanical stiffness of the locked plate, leading to plate bending. Use of a longer plate would have better distributed the stresses associated with weight-bearing at the fracture site, avoiding the complication seen in this case.

Indications for Locked Plate Fixation

The current indications for locked plate fixation include complex periarticular fractures, comminuted metaphyseal or diaphyseal fractures, periprosthetic fractures, and fractures occurring in poor quality bone.[4,8,19,24] Locked plates may also be used as an alternative to dual conventional plating techniques for bicondylar tibial plateau fractures.[8,28] Additional indications for locked plate systems include metaphyseal fractures of long bones in which intramedullary (IM) nail fixation may have a high likelihood of malalignment and for fixation after corrective osteotomy procedures.[8]

Laboratory Evaluation of Locked Plate Systems

Since the advent of locked plating systems, these constructs have been evaluated with varying results in a number of cadaveric models for a variety of fracture locations and patterns. In a comparison of locked plating with fixed angle blade plate fixation of surgical neck fractures of the proximal humerus, Siffri et al demonstrated that the locked plate provided significantly greater stability to torsional loads and a trend toward greater stability in response to bending loads ($P = 0.079$).[13] During cyclic loading of their cadaveric specimens, the locked plate construct resulted in significantly less loosening than their blade plate counterparts. Weinstein et al found a similar improved resistance to torsional loading with locked plating compared to angled blade plate fixation of simulated 3-part proximal humerus fractures.[16] Overall, the locked plate provided almost twice the torsional resistance of the angled blade plate with the most pronounced difference noted in the specimens with the lowest bone mineral density. On the basis of their data, the authors concluded that locked plate fixation of proximal humerus fractures is advantageous in the elderly, osteoporotic patients who typically sustain these fractures, potentially allowing for earlier postoperative rotational mobilization. Seide et al compared locked and unlocked plate fixation for simulated proximal humerus fractures and found that locked plate fixation was significantly stiffer and provided a 64% increase in ultimate failure strength.[12] Cyclic loading led to fixation failure in each of the specimens treated with unlocked constructs (range, 97,000 to 500,000 cycles), whereas none of the locked plate constructs failed at 1 million cycles. A similar improved fixation strength of locked plate constructs compared to conventional plating techniques was demonstrated by Walsh et al in a cadaveric 2-part proximal humerus fracture model.[15] The authors found a 23% increase in failure strength associated with locked plate fixation. Edwards et al compared the biomechanical properties of locked plate constructs and IM nails for the fixation of 2-part surgical neck fractures of the proximal humerus.[29] The authors found that in response to varus cantilever bending, the specimens treated with locked plating had significantly less fracture fragment displacement than those treated with IM fixation. Additionally, the locked plate provided significantly better resistance to torsional loads and was found to be overall a stiffer construct. On the basis of their data, they concluded that locked plate constructs for surgical neck fractures demonstrated superior biomechanical characteristics compared to IM nail fixation,.

Recent studies have compared locked plate constructs with conventional treatment modalities for the management of distal femur fractures. Zlowodzki et al evaluated the biomechanical characteristics of the Less Invasive Stabilization System (LISS; Synthes, Paoli, PA), angled blade plate, and retrograde IM nail, in distal femur fracture fixation.[17] In their cadaveric model, the locked LISS construct demonstrated greater fixation strength in response to axial loading compared to both the angle blade plate and IM nail. Lower resistance to torsional loads was noted with the LISS plate fixation; however, torsional load to failure for all of the tested treatment methods in this study occurred at loads much higher than those seen clinically. The same authors compared the locked LISS plating construct with a 95-degree angled blade plate for fixation of distal femur fractures in specimens selected for high bone mineral density.[30] In this specific subset, no difference was noted in the loads to failure between the 2 fixation techniques (mean load to failure: LISS 977 N; angled-blade plate, 901 N). In a similar cadaveric distal femur fracture model, Higgins et al found that, compared to fixation with an angled blade plate, locked plate fixation resulted in significantly less fracture fragment subsidence with cyclic loading and significantly greater ultimate load to failure.[31]

Ratcliff et al compared the mechanical stability of a laterally placed locked plate construct with a medially applied buttress plate for the fixation of a simulated medial tibial plateau fracture.[32] Although no significant difference was noted between fixation constructs with respect to displacement secondary to cyclic loading, the medial buttress plate resulted in significantly higher failure strength (4136 N compared to 2895 N; $P < 0.05$). Single lateral locked plating was compared to dual plating in the management of bicondylar tibial plateau fractures in a cadaveric model by Higgins et al.[33] The authors found that dual plate fixation permitted less medial fragment subsidence than the isolated lateral locked plate construct. Based on their data, the authors concluded that isolated laterally placed locked plates may not be the best fixation method for bicondylar tibial plateau fractures. Different results were reported by Gosling et al, in their evaluation of dual plating versus unilateral locked plating for bicondylar tibial plateau fractures.[34] Although higher elastic deformation was noted in the unilateral locked plating group, the authors found that vertical loads of 400–1600 Newtons resulted in similar irreversible fracture fragment subsidence with both fixation constructs.

In a biomechanical comparison between dorsal T versus volar fixed angle plating of distal radius fractures, Liporace et al., reported that the volar locked plate was stiffer than the dorsal plate with respect to both volar and ulnar loading.[10] It was also stiffer than the dorsal plate in all modes of axial loading with the exception of dorsal loading. Additionally, they noted a trend for increased axial stiffness of the volar locked plate after cyclic loading presumably due to compression of the locking screw against the subchondral bone. In a similar biomechanical study by Trease et al., dorsal and volar locked and non-locking plates were compared in a cadaveric distal radius fracture model with dorsal comminution.[35] The authors found no significant differences in stiffness or failure strength between volar locked and non-locked plates. Axial loading of their specimens demonstrated that the stiffness of dorsal locked plates was 50% greater than that of non-locked plates, but this difference failed to reach statistical significance. Load to failure testing showed that the failure strength of dorsal constructs (locked and non-locked) was significantly greater (53% higher) than that seen with volar constructs (locked and nonlocked).

In a cadaveric intaarticular calcaneus fracture model, Stoffel et al compared conventional nonlocking plates with locked plate fixation.[14] The locked plate constructs demonstrated significantly less plastic deformation with cyclic loading and higher ultimate failure strength compared to their nonlocking counterparts. On the basis of their data, the authors concluded that locked plate constructs provided a distinct advantage for fixation of calcaneus fractures, especially in osteoporotic patients. A cadaver model of Sanders type IIB calcaneus fractures was used by Redfern et al to compare the biomechanical properties of locked and nonlocked plating techniques.[11] The authors found that cyclic axial loading of the specimens treated with locked plate constructs resulted in a higher mean cycles to failure (3261 versus 2271 cycles); however, this difference did not reach statistical significance. In a sawbones calcaneus fracture model, Richter et al found that locked plate fixation resulted in significantly less fracture fragment displacement compared to traditional nonlocked plating.[36]

Clinical Studies with Locked Plate Fixation

Along with the laboratory testing of locked plate constructs, the recent literature has included a number of reports on the early clinical experience using this fixation technology for a variety of fracture patterns. Koukakis et al described their experience using the proximal humeral internal locked system (PHILOS) plate in the operative management of proximal humerus fractures.[37] Over a 3-year period, 20 patients with a mean age of 62 years had their fractures treated with this locked plate construct. The authors reported a 100% rate of fracture union in this cohort with a mean Constant shoulder score of 76.1% at 6 months of follow-up. Implant failure occurred in 1 case, with the plate pulling off the humeral shaft in an 82-year-old woman with a history of osteoporosis. Similar results with the PHILOS plate were reported by Bjorkenheim et al in their series of 72 patients treated over a 1-year period.[38] At 1 year of follow-up, the mean Constant shoulder score in their cohort was 77%. Screw failure with plate separation from the humeral shaft occurred in 2 cases, which the authors attributed to technical error (incorrect drill bit diameter). In a recent retrospective review of 32 patients with displaced 3- and 4-part proximal humerus fractures treated with the PHILOS plate, Moonot et al reported a 97% union rate.[39] At a mean follow-up of 11 months, the mean Constant shoulder score was 66.5%. Complications in this series included 1 malunion, 1 nonunion, and 1 case of distal screw failure leading to plate separation from the humeral shaft. No additional treatment was required in the single case of hardware failure secondary to maintenance of fracture site alignment.

Recent clinical studies on the efficacy of the LISS in the operative treatment of distal femur fractures have been reported. Weight and Collinge retrospectively evaluated the use of the LISS locked plating construct in 22 distal femur fractures in 21 patients.[40] All fractures achieved union at a mean of 13 weeks (range, 7 to 16 weeks) without the need for secondary intervention. There were no implant failures in this patient cohort; at a mean of 19 months of follow-up, knee range of motion was 5 to 114 degrees. Four patients (18%) had pain at follow-up, 3 of which required implant removal. In a similar retrospective evaluation of LISS plate fixation for 103 distal femur fractures, Kregor et al reported a 93% union rate without secondary bone grafting.[41] The remaining 7 cases went on to uneventful union subsequent to bone grafting procedures. At a mean follow-up of 14 months, the mean knee range of motion in this cohort was 1 to 109 degrees. Implant failure in the form of proximal screw loosening occurred in 5 cases, each requiring revision surgery.

Stannard et al recently reported on the use of the locked LISS plate for the operative management of complex tibial plateau fractures (OTA 41C).[42] In their series of 34 fractures in 33 patients, the authors reported a 100% union rate at a mean of 15.6 weeks (range, 6 to 28 weeks). Postoperative malalignment was noted in 2 patients (6%), 1 with 5 degrees of procurvatum and 1 with 4 degrees of valgus. At a mean of 21 months of follow-up, the mean knee range of motion in this series was 1 to 127 degrees, and the mean Lysholm knee score was 90 (range, 53 to 100). Ten patients had their plates removed subsequent to fracture healing (29%), 6 secondary to pain related to the implant, 3 to allow for ACL reconstruction, and 1 during surgical exploration for an associated peroneal nerve injury. Less promising results were reported by Gosling et al.[28] In a prospective evaluation of 69 complex tibial plateau fractures (OTA 41C) occurring in 68 patients, the authors reported postoperative malalignment in 23% of their cases, with the most common being at least 5 degrees of varus angulation. Additionally, secondary loss of reduction was noted to have developed in 9 cases (14%), with subsidence of the medial fracture fragment occurring most frequently.

Locked volar plating has become a commonly used treatment option for fractures of the distal radius. In a series of 41 patients whose unstable distal radius fractures were managed with volar locked plating, Rozental et al reported 100% of patients achieving good to excellent results.[43] Mean Disabilities of the Arm, Shoulder and Hand (DASH) score in this cohort was 14 (range, 0 to 74). A total of 9 complications were reported, including 4 cases of loss of fracture reduction secondary to dorsal collapse, 3 cases of tendon irritation requiring plate removal, 1 case of wound dehiscence, and 1 case of significant postoperative metacarpophalangeal joint stiffness. Arora et al prospectively evaluated 141 consecutive displaced distal radius fractures treated with volar locked plates.[44] The authors found that 60% of patients had a good to excellent outcome at a minimum of 1-year follow-up. Fracture union occurred in 100% of cases. Evaluation of postoperative range of motion in this cohort demonstrated extension that was 82% of the contralateral side, flexion that was 72% of the contralateral side, and pronation/supination that was 95% of the contralateral side. Complications were noted to have occurred in 27% of cases, with the most frequent being flexor and extensor tendon irritation.

Locked plating systems have also been used in the management of periprosthetic fractures around total knee and total hip replacements. Buttaro et al reported on 14 consecutive patients with Vancouver type B1 periprosthetic fractures of the femur.[45] Of 14 cases, 8 (57%) healed uneventfully at a mean of 5.4 months. Six of the locked plate constructs failed: 3 secondary to plate fracture and 3 secondary to plate pull-off. The authors noted that 5 of the 6 failures occurred in cases in which a supplemental cortical strut graft was not used. They concluded on the basis of their data that locked plating systems did not offer an advantage to other fixation strategies in the management of fractures distal to the tip of a stable femoral prosthesis. In a prospective evaluation of 22 periprosthetic supracondylar femur fractures treated with the Locking Condylar Plate (LCP), Ricci et al reported that 86% of cases went on to uneventful fracture union.[46] All 3 cases that did not heal occurred in patients with comorbid obesity and diabetes. Ninety-one percent of fractures had postoperative alignment within 5 degrees of normal, with 88% of patients returning to their baseline ambulatory status. Proximal screw failure occurred in 4 patients, with only 1 occurring when locking screws were used at these sites. Raab and Davis retrospectively evaluated locked plate fixation of 11 periprosthetic fractures occurring about total knee replacements.[47] At a mean of 21 weeks, 10 of 11 fractures healed, with 82% of cases healing in anatomical alignment. Knee range of motion at a mean of 1 year of follow up was 4 to 92 degrees. The authors reported a single case of implant failure that occurred secondary to the development of a nonunion.

Failure of Locked Plate Systems

The biomechanical properties of locked plate designs that make them attractive alternatives to conventional plates may also contribute to their failures in certain clinical situations. In a series of 169 fractures in 144 patients treated with the LCP, Sommer et al reported 27 complications (16.0% incidence), including 5 cases of implant loosening and 4 cases of implant breakage.[23] The authors attributed these implant failures to intraoperative technical errors, including the use of plates that were too short and those that did not have adequate spanning segments (empty screw holes) over the fracture site. Button et al reviewed 4 cases of LISS failure in distal femur fractures (18% incidence at their institution).[48] Of the four cases of failure, 2 involved fracture of the implant. Premature weightbearing before radiographic evidence of fracture healing was reported to have occurred in both cases, in addition to morbid obesity in 1 patient (revision angled blade plate failed as well). The 2 remaining cases of failure involved proximal screw pull-out. The authors attributed 1 of these failures to improper plate placement (too anterior), which may have led to insufficient proximal fixation. Vallier et al reported on failure of the (LCP) in 6 of 46 distal femur fractures (incidence of 13%) treated at a single institution.[49] In this series, 2 of the failures were plate breakage secondary to fatigue from motion through nonunions. The remaining 4 cases failed secondary to screw breakage at the screw-plate interface. Interestingly, in each of these reported cases of locked plate failure, the patients had metabolic factors that placed them at risk for delayed fracture healing (tobacco use, diabetes, obesity, osteoporosis, and open fractures).

Case Review of Failure Mechanisms

In the following section, we review four mechanisms of locked plate failures: (1) plate bending; (2) plate fracture; (3) plate pull-off; and (4) locking screw failure.

Plate Bending

The patient is a 63-year-old man who sustained a spiral periprosthetic left femur fracture 1 month after a total knee replacement secondary to a slip and fall. The fracture was managed with a 15-hole locked plate. Postoperative x-ray evaluation performed 3 weeks after plate placement demonstrated bending of the locked plate over the fracture site (Figure 1).

The stability of a locked plate construct is related to the length of the plate (cross-sectional area of the plate and material properties of the plate) and the screw-density about the fracture site. The longer the locked plate, the smaller the pullout force acting at the screw-bone interface secondary to an increased working leverage for each screw.[3,22] If the plate or spanning segment is too short, the working length for each screw is decreased, and applied loads will lead to high levels of strain at both the fracture site and the short spanning segment. When applied over a shorter plate or spanning segment, this bending moment increases the local strain experienced by the implant.[4,22] Repeated stresses concentrated over the fracture site at the most adjacent screw-bone interfaces and subsequently distributed along the construct both proximally and distally can exceed the mechanical stiffness of the plate and lead to implant deformation in response to the bending moment. The plastic deformation of the implant more evenly distributes the applied stresses, but it no longer provides the stable fixation required for maintenance of reduction, alignment, and subsequent fracture healing. It is likely that the use of a longer plate in this case would have better distributed the stresses associated with weightbearing experienced at and about the fracture site, avoiding the implant deformation that was observed.

Plate Fracture

The patient is a 48-year-old man who underwent right hip fusion at the age of 28. He sustained a subtrochanteric hip fracture after a fall, which was managed with a 12-hole locked plate construct. Two weeks after fracture fixation, the patient presented with significant right hip pain and inability to bear weight. X-ray evaluation demonstrated implant failure with fracture of the plate over the fracture site (Figure 2).

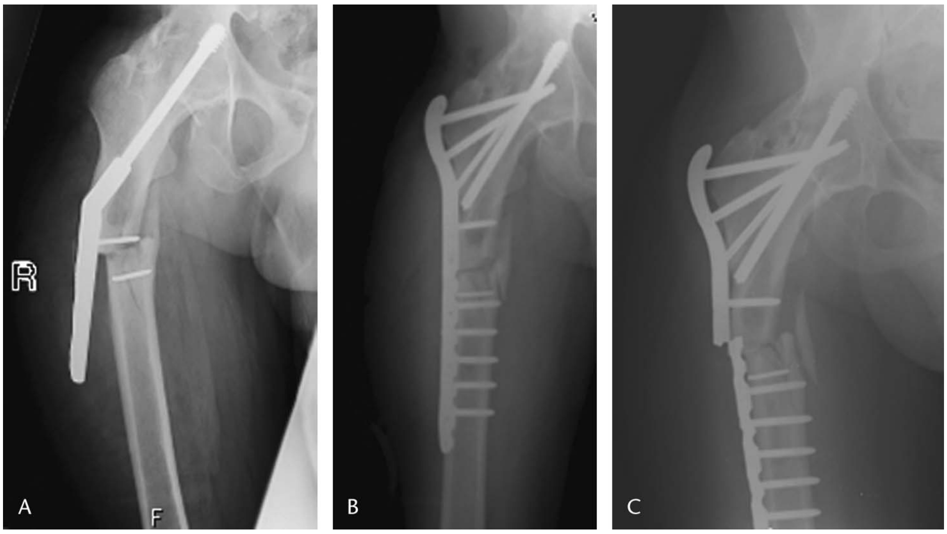

FIGURE 2. Example of plate fracture that occurred in a 48-year-old man treated for a right subtrochanteric hip fracture after a previous hip fusion (A). The fracture was treated with a 12-hole locked plate construct (B). Two weeks postoperatively, the patient presented with increased right hip pain and inability to bear weight. As seen on the (C) anteroposterior x-ray, the locked plate fractured over the fracture site. Use of a longer implant with an adequate spanning segment would have improved the distribution of load, avoiding stress concentration and subsequent plate fracture.

Fracture of the locked plate with physiologic loading appears to also occur as a function of stress experienced across the fracture site. Once again, if the segment spanning the fracture site is too short and the locked plate is not long enough to adequately distribute the applied load proximally and distally, the stress concentration seen in the spanning segment of the plate may lead to cyclic deformation, implant fatigue, and eventual implant fracture. Similar to the previous case of plate-bending, a longer locked plate with an adequate spanning segment without screws would have improved the ability of the construct to more evenly distribute loads, avoiding the progression from deformation to implant fracture. As reported by Vallier et al, implant fracture may also occur secondary to fatigue occurring through a nonunion site.[49] Early identification of a nonunion and appropriate management (bone grafting) may prevent the development of this potential complication.

Construct Pull-Out

The patient is a 55-year-old right-hand dominant man who sustained a right 2-part proximal humerus fracture after a fall off a stepstool. The fracture was managed with a 3-hole locked plate incorporating 6 screws in the humeral head. At the 6-week postoperative visit, the patient reported right shoulder pain prompting x-ray evaluation. Radiographs demonstrated implant failure, with the screws pulling out of the humeral head (Figure 3).

FIGURE 3. Example of construct pullout that occurred in a 55-year-old man who sustained a right 2-part proximal humerus fracture after a fall from a standing height as seen on the (A) anteroposterior and (B) axillary views. Intraoperative (C) anteroposterior and (D) axillary views demonstrate fracture fixation performed with a proximal humerus locking plate that included 6 screws in the humeral head. At the 6-week follow-up visit, the patient reported pain in his right shoulder. As seen on the (E) anteroposterior x-ray, implant failure occurred with construct pullout from the humeral head. In this case, poor bone stock and inadequate screw purchase in the humeral head did not provide enough bony fixation to absorb the bending and torsional loads associated with early range of motion exercises. Placement of additional screws peripheral to the plate to augment the fixation provided by the locked plate may have avoided the development of this complication.

This locked plate design may restrict the ability of the surgeon to optimally place the screws into the humeral head. An intentional design compromise meant to facilitate the reconstruction of proximal humeral anatomy based on an idealized humeral model led to obligate screw angles that can prevent adequate fixation of the humeral head fragment. In this case example, inadequate bone stock and inadequate screw purchase did not allow for a sufficient amount of bone to remain secured by the screws. Compressive stresses between the screws and the bone of the humeral head were not sufficient to overcome the torsional and bending loads acting at the fracture site as the patient began range of motion exercises. It is possible that in some cases, the placement of additional screws peripheral to the plate may augment fracture fixation limiting the impact of excessive torsional and bending loads.

Screw Head Failure

The patient is a 54-year-old man with a medical history significant for diabetes. He sustained a comminuted left distal metadiaphyseal fracture of the tibia after a twisting injury to the lower extremity during a fall. He underwent an uncomplicated open reduction and internal fixation using a medial locked plate construct with a lag screw placed outside the plate. The fracture progressed to nonunion as documented by a persistent fracture line without evidence of progressive healing by 4 months. Nine months postoperatively, before undergoing planned revision surgery, he presented with increased pain in the right lower leg and was unable to bear weight. X-ray evaluation demonstrated failure of the distal 2 locking screws with the heads sheared off (Figure 4).

It is likely that the nonunion in this patient developed secondary to a lack of adequate compression at the fracture site during the initial open reduction and internal fixation. The stiffness of the locked plate construct maintained this fracture site gap, prohibiting bony healing. Repetitive motion of the distal fragment with weightbearing through the nonunion site created significant shear stresses on the distal aspect of the fixation. When the applied stresses exceeded the inherent material properties of the distal 2 locking screws, the screws broke at this area of stress concentration. With significantly comminuted fractures, adequate compression at the fracture site must be achieved before locked plate application because the stiffness of this construct may contribute to the maintenance of fracture site gapping and the development of a nonunion. Additionally, complete insertion and locking of the screw within the plate will help eliminate excessive stresses at the head-shaft junction.

FIGURE 4. Example of screw head failure seen in a 54-year-old man who sustained a comminuted distal tibial metadiaphyseal fracture managed with a medial periarticular locked plate construct with a lag screw placed outside the plate as seen on the (A) anteroposterior x-ray. At his 9-month follow-up visit, an (B) anteroposterior x-ray demonstrated nonunion of the distal tibia fracture with failure of the distal locking screws at the screw head-shaft junction. Repetitive motion of the distal fragment through the nonunion site led to shear stresses on the distal screws. In this comminuted fracture pattern, better compression at the fracture site before locked plate application may have prevented the development of nonunion and the associated stresses on the construct seen with repetitive loading. Additionally, complete insertion and locking of the screws within the plate helps avoid the development of excessive stresses at the screw head-shaft junction.

SUMMARY

Locked plate technology was developed as a consequence of improved understanding of the roles of tissue vascularity and gap strain in fracture healing. The relative stability provided by the locked plate allows for optimization of gap strains at the fracture site, favoring secondary bone healing through callus over primary bone healing.[3,4] Currently used for complex periarticular fractures and fractures occurring in poor quality bone, locked plates have been shown to be clinically effective with low complication rates.

In the current paper, the biomechanics of locked plate technology was reviewed, and laboratory and clinical comparisons to conventional fixation techniques and potential mechanisms of locked plate failure that have been observed clinically were identified. An understanding of the fixation principles of locked plating systems may enable the surgeon to avoid the development of implant-related complications and benefit from the biomechanical advantages afforded by these constructs.

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