The Evolution of Locked Plates

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Introduction

Our purpose is to review the history of locked plates and the current recommendations for the use of those devices and to look toward future trends in the clinical application of locked plates. We will discuss (1) the impetus for the locked (fixed-angle) plate design, (2) current indications and design trends, (3) the latest clinical and biomechanical data, (4) shortcomings of locked (fixed-angle) plates, and (5) future applications and directions for locked (fixed-angle) plates.

Impetus and Indications for Locked (Fixed-Angle) Plates

Since their initial introduction in the late nineteenth century and their subsequent popularization by Danis[1-3] and the Arbeitsgemeinschaft fur Osteosynthesefragen (AO) group in the 1960s, conventional nonlocked plates have proven, over time, to successfully stabilize many types of fractures and osteotomy sites. The plate-screw-bone construct must resist physiological loads to allow fracture union by limiting fracture gap stress, provide sufficient stability to permit early limb motion, and not fail before fracture union occurs. Additionally, for optimal clinical results, disruption of the bone blood supply by the plate-screw-bone construct should be minimized. To accomplish this goal, there should be minimal operative dissection and periosteal contact to promote bone union[4,5]. Ideally, the plate-screw-bone construct will permit the restoration of the mechanical limb alignment and reestablish joint congruity to within <2 mm[2,6,7]. Finally, to be successful, plate fixation must provide reproducible results, must be simple to perform, and must have broad clinical applicability.

Fixation with conventional compression plates, although for the most part successful, has its limitations. Figure 1 demonstrates one attempt to counter the limitations associated with the use of conventional nonlocked plates. To achieve fracture stability, the axial, torsional, and three-point bending forces must be neutralized (Fig. 2). With the use of conventional nonlocked plates, force friction between the plate and the bone counters the external forces experienced by the plate-screw-bone construct (Fig. 3)[8]. Therefore, the ability of conventional plates to achieve stability is limited by screw torque. Osteoporosis, cancellous bone, comminution, and/or pathological bone can prevent adequate thread purchase to allow the development of sufficient torque (1.5 N) to establish stability[8,9]. The excessive soft-tissue stripping necessary to improve the friction coefficient between the plate and the bone can compromise the blood supply to bone fragments and soft-tissue flaps. Furthermore, limiting exposure has the additional benefit of improving the cosmetic result.

There have been multiple attempts to improve fixation of conventional plates to compromised bone. These have in-

Fig. 1

Radiograph of a twenty-eight-year-old man with a fracture with massive bone loss in the metaphyseal region; bicondylar plates were necessary to achieve stability. The extensive soft-tissue stripping needed to perform the operation compromised the blood supply to the fracture, which was already at high risk for healing complications.

TABLE I Specific Indications for Different Techniques

Indication	Compression	Bridging	Combination
Diaphyseal fractures	Yes	Yes (3-4 screw holes empty over fracture)	
Metaphyseal fractures	Yes	Yes (3-4 screw holes empty over fracture)	
Multifragmentary diaphyseal fractures		Yes (near far/far near)	
Multifragmentary metaphyseal fractures		Yes (near far/far near)	
Osteotomies	Yes	Yes	
Articular fractures	Anatomical reduction		
Segmental with two different fracture patterns			Compression/bridging
Articular fractures with multifragmentary metaphyseal or diaphyseal fractures			Compression articular fragments/bridging

cluded the use of cement to improve screw torque (Figs. 4-A and 4-B)[10]. Schuhli nuts (Figs. 5-A, 5-B, and 5-C)[10] and Zespol plates[11] were used in early attempts to convert a conventional plate into a fixed-angle device whereby the plate functions like an "internal fixator." These early attempts were refined by the AO group and were introduced as the PC-Fix[12,13] and Less Invasive Stabilization System (LISS plate) (Synthes, Paoli, Pennsylvania)[14-16]. The clinical successes of these plates led to the introduction of the Locked Compression Plate (Synthes)[17,18] and a recent proliferation of locked-plate designs by several manufacturers.

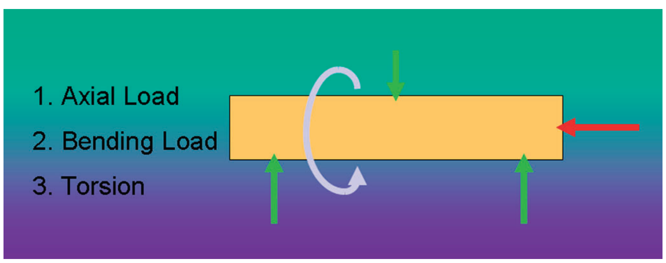

Fig. 2
The forces that must be overcome by any method of fracture fixation.

A desire to preserve the blood supply to the bone by eliminating, or at least reducing, plate contact (Fig. 6) with the periosteum provided the impetus for the development of the early fixed-angle-plate systems. Designers postulated that, by preserving the blood supply to bone, it would be possible to minimize or avoid refracture after hardware removal, development of infection in a sequestrum under the deep surface of the plate, delayed union, and nonunion[5,19].

The fundamental principles of external fixators apply to locked plates and need to be respected to avoid complications. The stiffness provided by external fixators increases as the connecting bar is moved closer to the bone and the amount of pin spread is increased. Locked plates are thus comparable with extremely rigid external fixators and run the risk of becoming "nonunion generators." However, unlike external

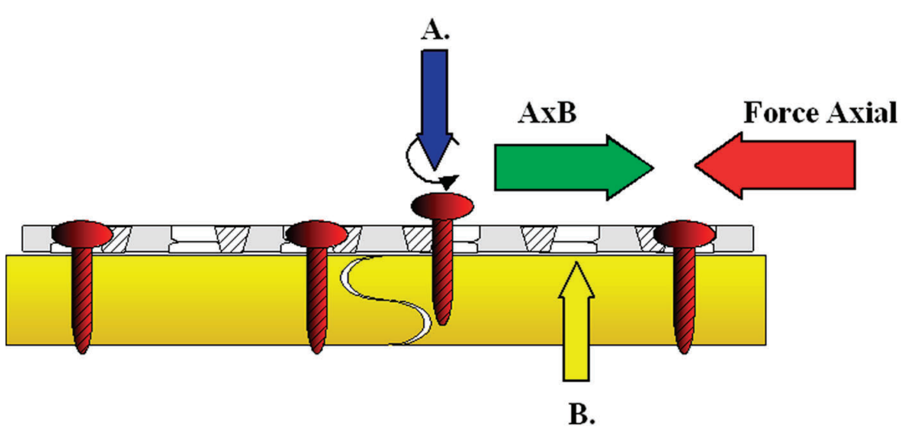

Fig. 3
Axial force is countered during compression plate fixation by the product of A (the normal force provided by screw torque) and B (the coefficient of friction between the plate and bone).

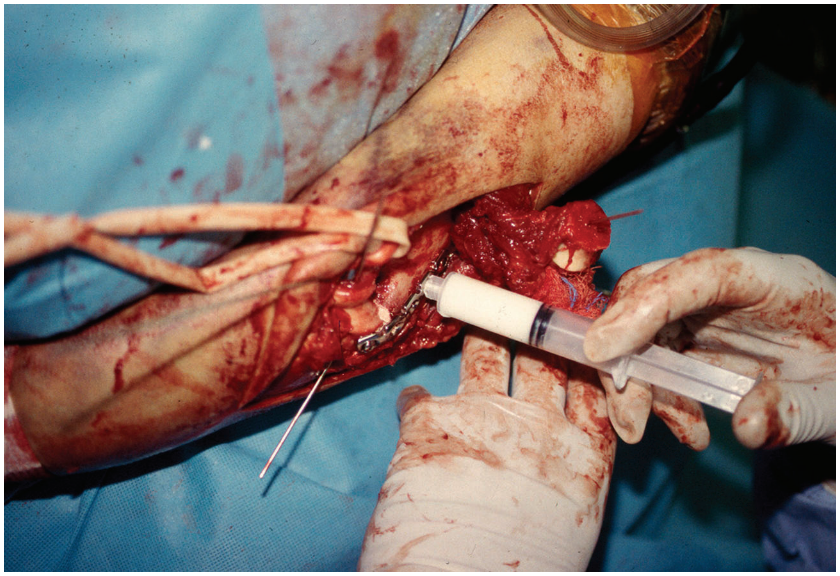
Fig. 4-A

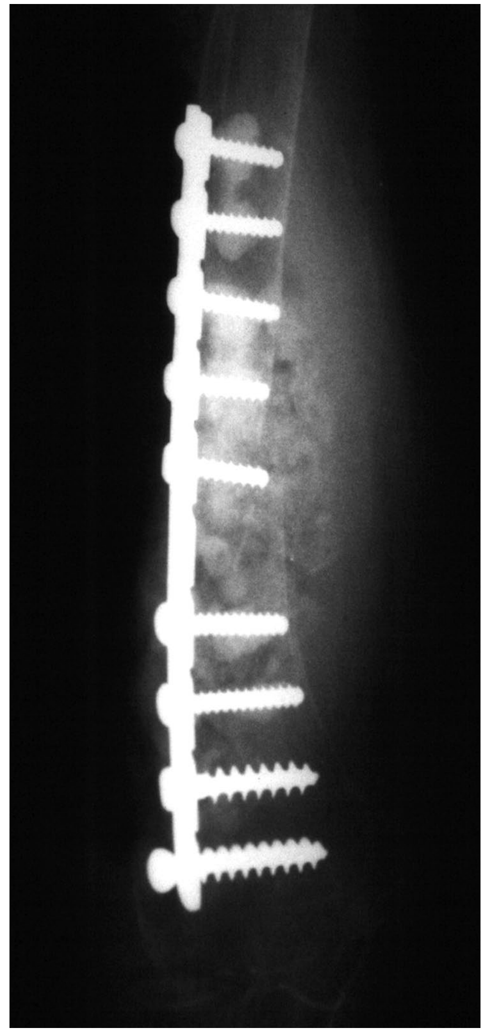
Fig. 4-B

Fig. 4-A Injection of methylmethacrylate into the drill hole to augment screw fixation. **Fig. 4-B** Tightening of the screws into set cement improves fixation in pathological bone by allowing the development of increased screw torque.

fixators, they are very difficult to dynamize. Biomechanical research has supported this principle with respect to the fracture gap and screw stress when locked plates are used[20]. When locked plates are used in a bridging mode, they should be predynamized by allowing at least two empty screw holes over the fracture gap (Fig. 7). This increases the working length of the plate and decreases internal stress in the plate[20,21]. Additionally, an increased working length actually decreases stress in the screws when there is a 1-mm fracture gap. The working length has no effect on screw stress or plate stress when the fracture gap is >1 mm, and the bone cannot share the load; in this case, the plate is in a bridging mode[20]. Plate-bone distance has been shown to alter the strength of fixation in biomechanical models[22]. Increasing the plate-bone distance decreases axial and torsional stiffness, whereas increasing the length of the plate increases only axial stiffness and has no effect on torsional stiffness[20,22].

The optimum screw ratio (the number of screws used for fixation divided by the number of available screw holes—for example, the screw ratio for a ten-hole plate with five screws is 0.5) and the appropriate use of bicortical fixation when locked plates are utilized have not been well researched in the clinical setting. However, there is good biomechanical data to guide the achievement of the appropriate screw ratio. The recommended screw ratio is 0.4 to 0.5 for bridging fixation with three or four screws on either side of the fracture gap[21,23]. The use of unicortical screws is supported by the fact that, during axial loading and three-point-bending tests of plate-unicortical screw-bone constructs in normal bone, unicortical screws provided fixation strength in excess of physiological loads[22,23]. Additionally, unicortical screws are easier to place percutaneously, and bicortically placed screws strip the near cortex as they are advanced into the far cortex, effectively achieving only unicortical purchase.

Axial stability provided by locked screws leads to a mechanism of screw-purchase failure that is fundamentally different from that of conventional unlocked screws (Fig. 8). Fixed-angle screws effectively convert forces experienced during three-point bending and axial loading to compression. All screws effectively act together in parallel, whereas conven-

Fig. 5-A

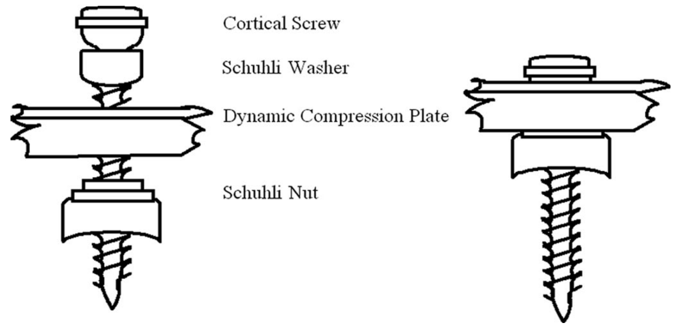

Fig. 5-B

Fig. 5-C

Figs. 5-A, 5-B, and 5-C Schuhli nuts turn a conventional dynamic compression plate into a fixed-angle device. **Fig. 5-A** Plate and screws with the central Schuhli nut expanded. **Fig. 5-B** Schematic of the Schuhli nut. **Fig. 5-C** Schuhli nut locks plate to screw, creating a fixed-angle device.

tional screws do not. Conventional screws fail by toggling within the bone and act in series, each screw functioning effectively alone[24]. Unicortical screws are severely limited in their ability to resist torsional loads because, in torsional loading, working length is paramount and cortical thickness becomes critical for a unicortical screw to resist torsional loads. As demonstrated in Figure 9, the advantages of bicortical fixation with regard to screw working length far outweigh the advantages conferred by healthy cortical bone. In situations where high torsional loads are expected, bicortical locked screws should be employed[22].

Locked plates have become an attractive alternative to conventional plates as they can be used as "bridge plates" to preserve fragmentary blood supply, they provide fixed angular stability with the potential for improved fixation in osteoporotic bone, and they reduce the risk of primary loss of reduction as exact plate-contouring is not required. The current indications for use of a locked plate, as defined by Gautier and Sommer[21] on the basis of biomechanical and limited clinical data, are listed in Table I. Locked screws can aug-

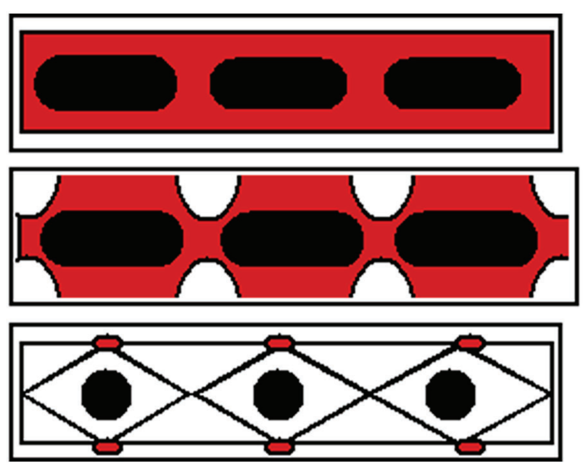

Fig. 6

Reduction in plate-bone contact. From top to bottom: the dynamic compression plate, the limited-contact dynamic compression plate, and the point contact fixator. The contact surface is red.

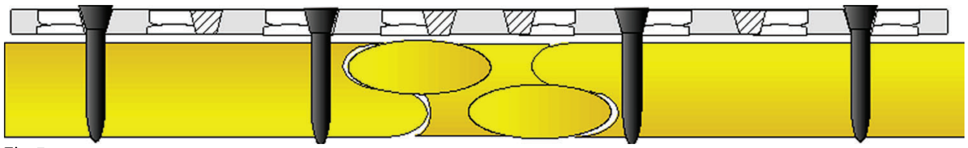

Fig. 7

Locked screws are used when a bridge-plate technique is applied to span an area of comminution. The omission of one screw on either side of the fracture decreases the bending stiffness of the plate by approximately 50%[20].

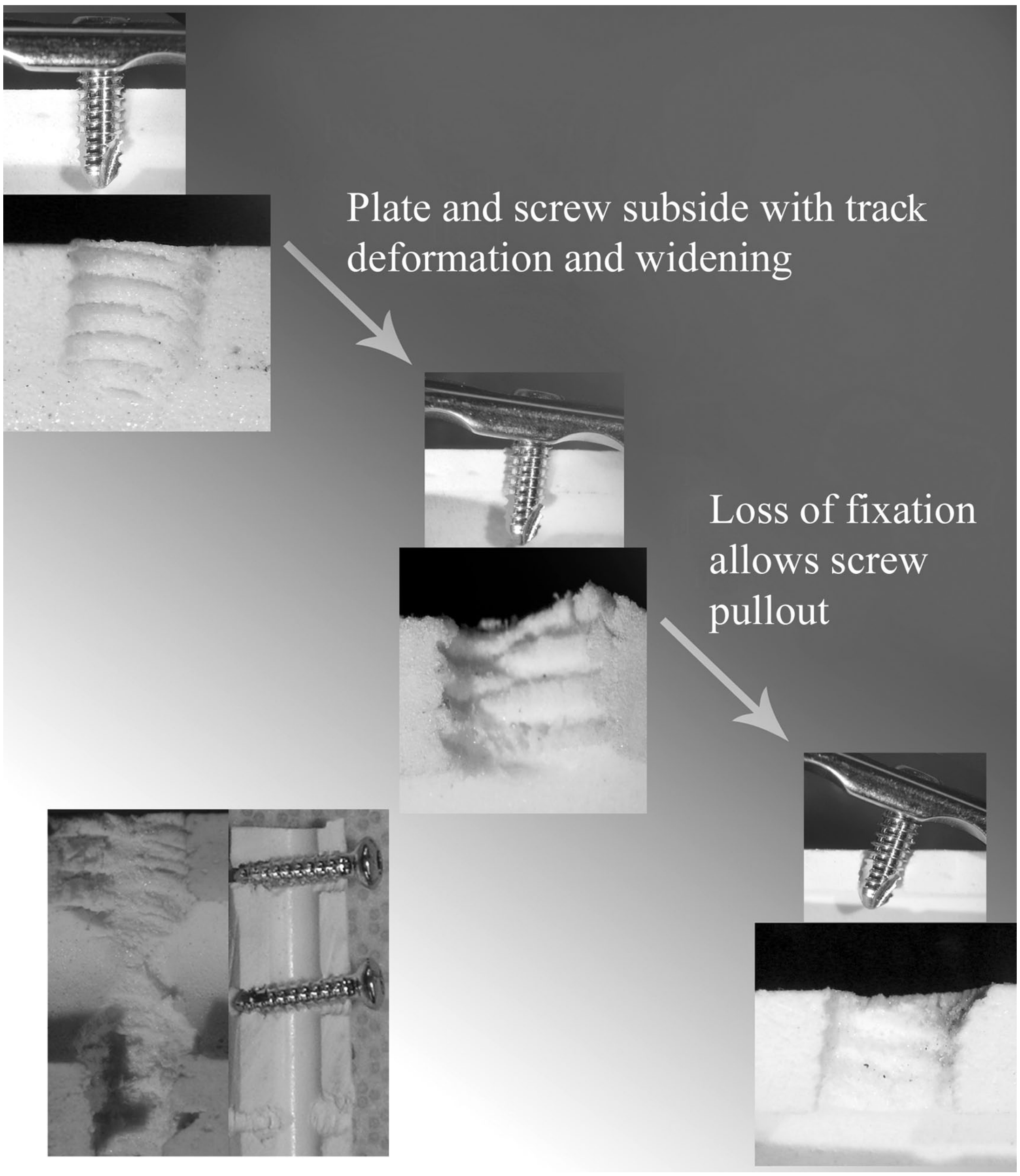

Fig. 8

Deformation of the screw-hole track after application of a three-point-bending load to failure. The screw pulls out from the plate as the screw track deforms, and the plate-screw construct fails en masse. The inset on the lower left shows toggling of unlocked screws within the screw track with axial loading, resulting in failure during three-point-bending load despite bicortical purchase.

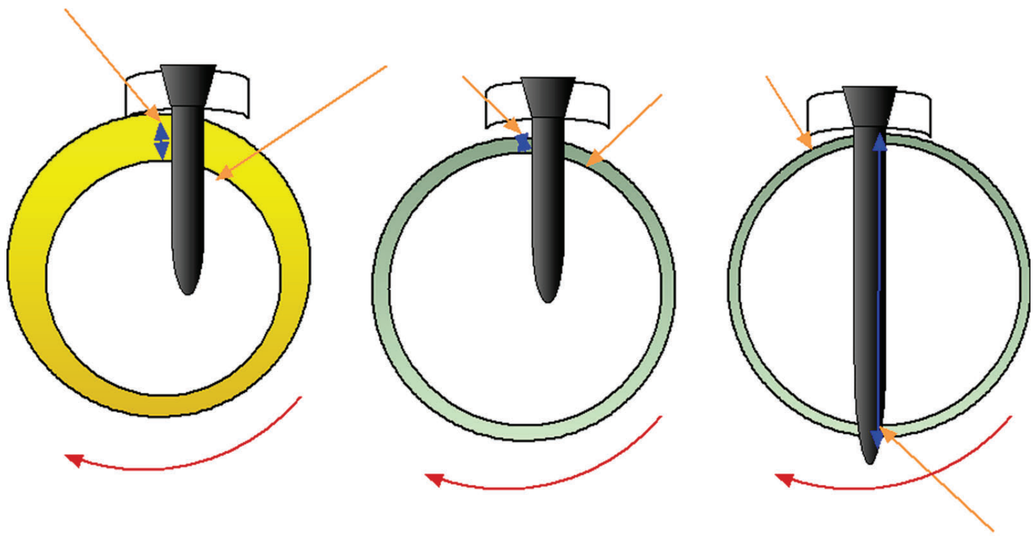

Fig. 9

Cross sections of diaphyseal bone showing the difference in the working length (blue arrowheads) of unicortical screws in normal (yellow) bone compared with osteoporotic (green) bone. In normal bone, the working length may be sufficient to resist applied torque (red arrows), whereas, in osteoporotic bone, bicortical screws provide a much greater screw working length and improved resistance to torsional stress at the screw-bone interface (orange arrows).

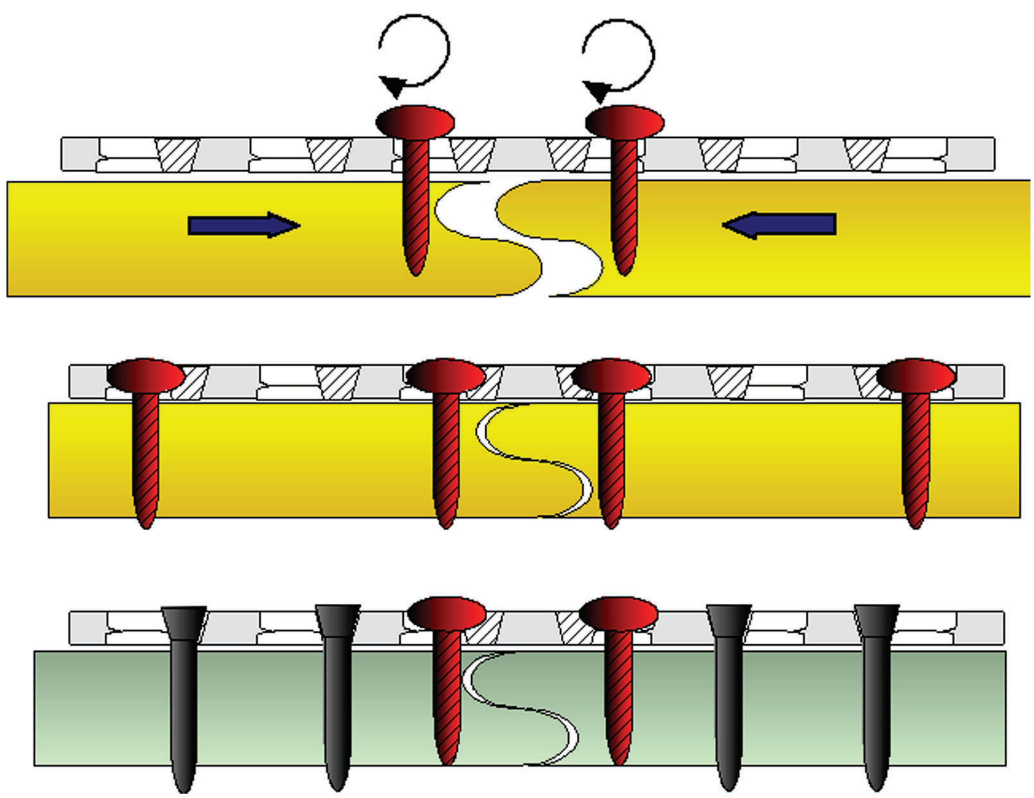

Fig. 10-A

Figs. 10-A, 10-B, and 10-C Guidelines for the appropriate use of standard or locked plates, or plates combining the two fixation modes[16]. **Fig. 10-A** Compression principle with use of the eccentric screw technique in bone of normal quality (yellow) and combined with locked screws in poor-quality bone (green). Bicortical screws are used for improved torsional control.

ment standard compression screws in compression plates, resulting in hybrid fixation, in osteoporotic bone (Figs. 10-A, 10-B, and 10-C).

Locked plates facilitate two-column support and have been clinically successful in situations in which dual compression plates were previously indicated, such as in the proximal part of the tibia, distal part of the tibia, and distal part of the femur (Figs. 11-A and 11-B)[14,25-27]. Similarly, locked plates have been excellent for stabilization of challenging fractures in osteoporotic bone, particularly those of the proximal part of the humerus, distal part of the radius, and distal part of the humerus[28-30]. Since they do not depend on friction fit between the plate and bone for stability, locked plates show promise for fixation of malunions, previously fractured bone, and pathological bone[31-33].

The use of locked plates and percutaneous techniques have evolved together while remaining true to the AO principles of internal fixation. Percutaneous fracture fixation employs three basic principles: (1) percutaneous reduction, (2) extraperiosteal placement of the plates, and (3) bridging fix-

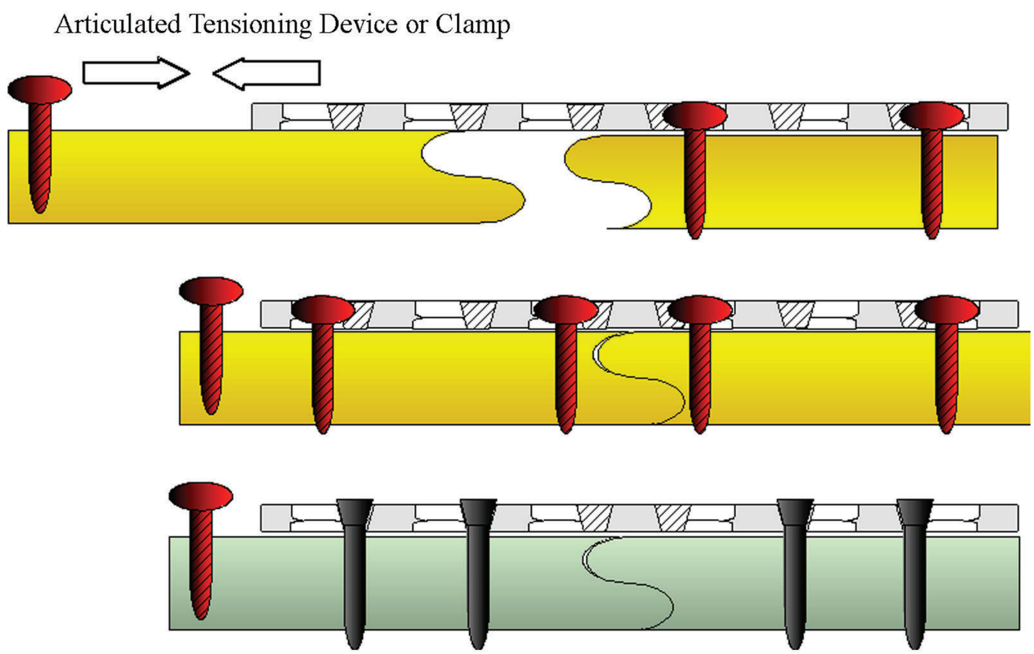

Fig. 10-B

Compression principle with use of an articulated tension device; standard nonlocked screws are employed in normal-quality bone (yellow) and locked screws, in poor-quality bone (green). Again, bicortical screws are used for torsional control.

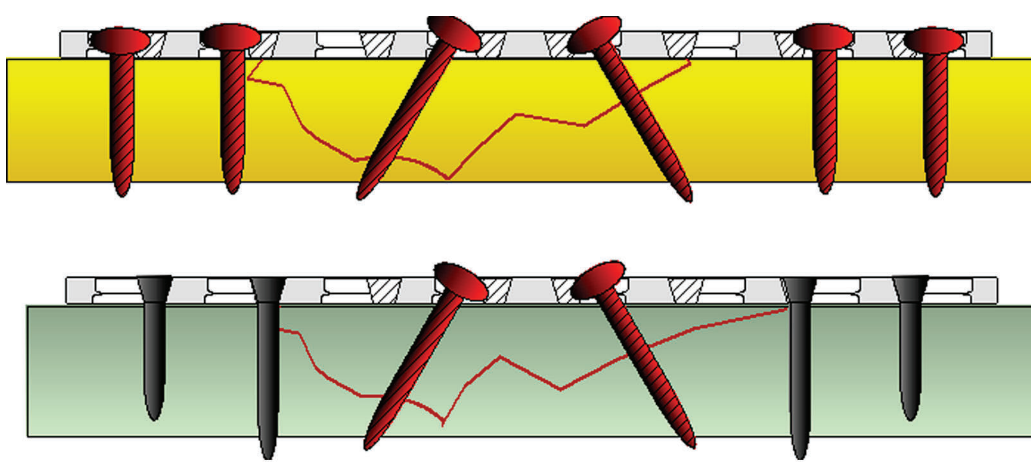

Fig. 10-C

Combination, or hybrid, use of standard compression screws and locked screws to improve the fixation in poor-quality bone (green) when a neutralization plate is employed.

Fig. 11-A

Fig. 11-B

Figs. 11-A and 11-B Clinical application of locked bridging fixation in a forty-six-year-old morbidly obese woman who required bicolumnar support. **Fig. 11-A** Extra-articular distal femoral fracture. **Fig. 11-B** Initial stabilization of the distal femoral fracture with a locked plate.

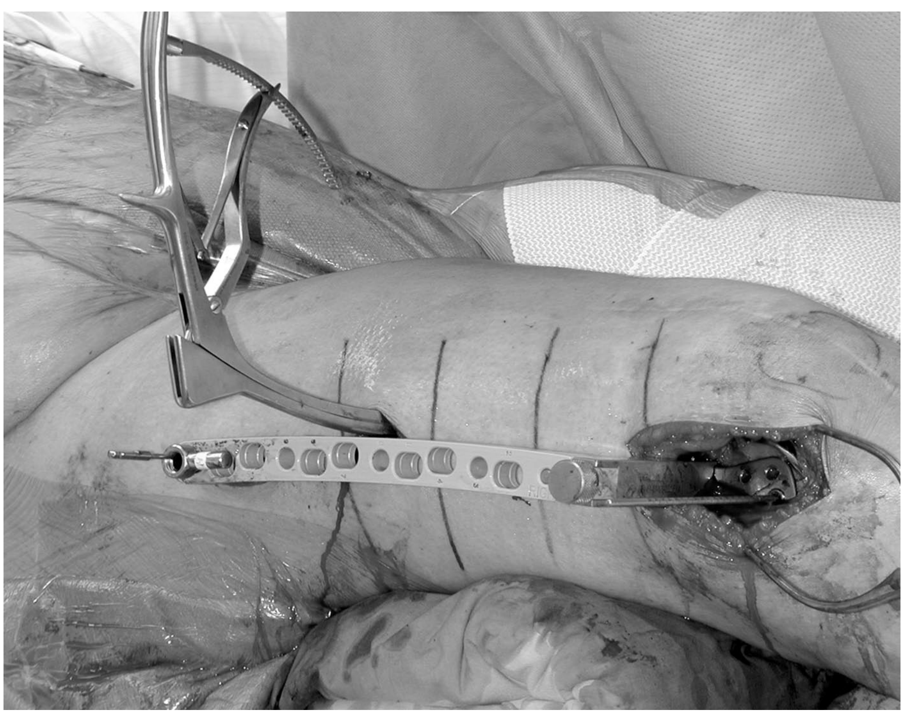

Fig. 12

Percutaneous fixation with locked plates is made easier with radiolucent guides to direct screw placement. Reduction is still performed percutaneously with use of fluoroscopy-guided lag screws and clamps to restore the articular component of the fracture. The plates are then placed with the aid of the jig and clamps submuscularly through small incisions while satisfactory anatomical alignment is confirmed radiographically.

Fig. 13-A

Fig. 13-B

Figs. 13-A through 13-D This six-year-old girl sustained a femoral fracture, which was initially treated in a spica cast. **Figs. 13-A and 13-B** Angulation and shortening were progressive over a three-week period.

ation. The overlying principle is to preserve the blood supply and minimize soft-tissue injury. While percutaneous fixation can be achieved with devices such as the dynamic condylar screw, proximal fragment stability is hard to optimize because the plate is not in direct contact with the bone and poor bone quality may not afford sufficient screw purchase. The locked plate with a percutaneous guide solves these problems (Fig. 12).

Although there are no absolute contraindications to the use of locked plates, there are clinical situations for which locked plates are unnecessary. These include cases with good-quality bone in which compression of a simple diaphyseal fracture is indicated and those in which the local anatomy prohibits percutaneous plate application (for example, a midshaft fracture of the humerus). Furthermore, locked plates are for the most part unnecessary for the fixation of pelvic and acetabular fractures. Additionally, a locked plate is unnecessary for a calcaneal fracture that is immobilized in a patient who remains non-weight-bearing for an extended period of time after fixation.

As locked plates have permeated orthopaedics, surgeons are becoming more comfortable with their use. Locked plates are being applied in lieu of intramedullary nails for stabilization and during the consolidation phase of limb-lengthening, and they are being substituted for blade-plates and dynamic condylar plates to stabilize osteotomy sites after correction of deformity. Additionally, locked plates are being used for the fixation of diaphyseal fractures in children (Figs. 13-A through 13-D) because of the ease of percutaneous application and the ability to avoid the physis.

As the use of locked plates has expanded and the numbers of fractures fixed with these plates have increased, clinical failures have been seen. The plates can fail when physiological loads are outside plate-design parameters. The locked screws

Fig. 13-C

Fig. 13-D

Figs. 13-C and 13-D Fixation with a percutaneous locked plate permitted toe-touch weight-bearing, and uncomplicated union of the fracture resulted.

Fig. 14-A

Fig. 14-B

Figs. 14-A and 14-B A seventy-four-year-old man sustained a proximal humeral fracture in a fall. **Fig. 14-A** Initial fixation with a proximal humeral locking plate permitted early pendulum exercises. **Fig. 14-B** The patient returned to the clinic at six weeks with pain in the right shoulder. Radiographs demonstrated loss of fixation in the proximal part of the humerus.

can disengage from the plate secondary to failure of the screw to seat into the plate properly as a result of cross-threading (where the screw threads and the plate threads are not collinear) or when insufficient screw torque is used to engage the screw threads into the plate threads. Additionally, like all mechanical devices, the screws can break or disengage from the plate under excessive cyclical loading. Despite an excellent "feel" in the operating theater, locked plates may cease providing fragment fixation as a result of exceedingly poor bone quality (Figs. 14-A and 14-B). Nonunion and malunion can still occur with the use of locked plates.

Future Directions

New plate designs continue to emerge in response to the need to improve current designs and fill niche markets. The development of plates that permit the surgeon to determine screw placement and still maintain the benefits of a fixed-angle device is ongoing, despite the fact that initial variable-angle fixed-angle devices were plagued with failures of the locking mechanism.

Additional clinical research is needed to confirm that the biomechanical benefits of fixed-angle plates documented in the laboratory setting are borne out clinically in the form of reduced complications, improved functional outcomes, and greater patient satisfaction. These clinical data will be crucial in the determination of the cost-effectiveness of locked plates. We still do not know the specific clinical situations in which the use of locked plates, with their additional cost, is justified. ■

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