The Influence of Fracture Fixation Biomechanics on Fracture Healing

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Numerous studies have shown that the mechanical conditions at the fracture site, principally the fixation stability, influences callus formation during fracture healing. This article reviews the factors that can influence the mechanics of locked plate fixation and its effect on the subsequent fracture healing.

Locked plates offer significant advantages over conventional plates, including improved fixation in osteoporotic bone. They were developed to overcome the problem of early deleterious instability following the use of traditional internal fixation plates. Locked plates have seen widespread adoption, and their clinical use has expanded to include simple fractures, which traditionally have been successfully managed with nonlocked plates.

Locked plates are often applied minimally invasive to minimize additional soft tissue disruption and devascularization of the fracture site. In this method, the plates often function as bridging constructs, without interfragmentary compression of the fracture site. In the absence of a direct reduction with rigid interfragmentary compression, these constructs heal by secondary fracture healing with callus formation. Secondary fracture healing requires some degree of interfragmentary motion at the fracture site. Recently, investigators have expressed concerns that some locked plate fixation constructs may be too stiff, leading to nonunion development (Figure 1).

Direct and Indirect Fracture Healing

The type of fracture healing that occurs depends on the mechanical stability present at the fracture site. Fractures treated with open reduction in which interfragmentary compression is achieved, such as with a lag screw or with a plate placed in compression mode, will heal by primary or direct fracture healing. The fracture fixation in this situation provides absolute stability. There is no motion at the fracture site, and no callus is formed. The fracture heals through the formation of osteonal cutting cones and Haversion remodeling of the compressed cortical bone.

In contrast, motion will occur at the fracture site in fractures treated with a cast or brace, an intramedullary nail, or a plate placed in a bridging mode. The fracture fixation in this situation provides relative stability and will heal with cal-
lus formation. Fractures treated with this more flexible fixation heal through secondary or indirect fracture healing. This process is similar to embryologic bone development in that initially a cartilage precursor is produced, which is then secondarily converted to bone.

The fracture pattern determines the ideal method of fixation for fracture healing. Simple fractures, when feasible, may be best treated by direct reduction with interfragmentary compression. The relative stability provided by this method minimizes interfragmentary motion and allows the fracture to heal by primary or direct fracture healing. In contrast, a highly comminuted fracture is best treated by indirect reduction with bridging fixation using a plate, intramedullary nail, or external fixator. The fracture pattern determines the ideal method of fixation for fracture healing. Simple fractures, when feasible, may be best treated by direct reduction with interfragmentary compression. The relative stability provided by this method minimizes interfragmentary motion and allows the fracture to heal by primary or direct fracture healing.

**STRAIN THEORY AND FRACTURE HEALING**

Perren introduced the importance of strain in fracture healing. Fracture gap strain is defined as the relative change in the fracture gap (ΔL) divided by the original fracture gap (L) (Figure 2). Tissue cannot be produced when strain conditions exceed the tissue strain tolerance. It is accepted that cortical bone can tolerate only 2% strain. Rigid internal compression fixation, which minimizes strain, will lead to primary or direct fracture healing. Lamellar bone can tolerate up to 10% strain, and when this relative stability is present, the fracture heals with callus or secondary fracture healing. Fracture healing will not occur when the strain at a fracture gap exceeds 10%. Comminuted fractures can tolerate more motion than simple fractures, since in a comminuted fracture the overall motion is shared among many fracture gaps (Figure 3).

**LOCKED PLATES**

Locked plates are often applied in a minimally invasive method and function in a bridging mode. Because locked plates provide a rigid plate-screw connection, they limit motion at the fracture gap directly beneath the plate. Whatever near cortex fracture gap is present at the time of plate application remains constant.

In contrast, because the flexibility of the plate permits some bending motion, some interfragmentary motion can occur in the fracture gap at the far cortex stimulating callus formation (Figures 4, 5). However, if the plate is rigid, even interfragmentary motion at the far cortex may be insufficient to promote optimal callus formation.

**PLATE LENGTH AND SCREW POSITION**

Varying the plate length and screw position can affect the mechanical stiffness of the fix-
trauma update

Figure 4: Axial loading can produce a bending moment on a locked plate. Micromotion at the fracture gap is greatest at the far cortex (dashed lines), while the fracture gap remains distracted at the near cortex.

Axial loading of locked plate constructs is mainly influenced by the working length of the plate. The working length of a plate is defined as the distance across a fracture site between the 2 nearest points where the bone is fixed to the plate, eg, the distance between the 2 screws closest to the fracture (Figure 1).

The disadvantage of placing screws close to the fracture site is the potential to create stress concentration with the risk of plate fracture (Figure 1). Placing screws farther from the fracture site can better distribute the stress the plate experiences and decrease the risk for plate fatigue failure.

The addition of >3 screws per fragment does not significantly impact the plate construct stiffness in axial loading. Adding an additional screw nearest to the fracture site provides the greatest increase in axial stiffness.

Figure 5: Limited callus is seen 3 months following minimally invasive plate fixation with a locked plate in a 73-year-old woman who sustained a comminuted supracondylar femur shaft fracture (A). At 6 months, abundant bridging callus can be seen at the far cortex, but there is no significant callus present at the near cortex (B).

EXPERIMENTAL METHODS TO REDUCE LOCKED PLATE STIFFNESS

Because of concerns that locked plates may not allow sufficient fracture site micromotion, especially at the near cortex, investigators have explored methods to increase the fracture gap micromotion with axial loading.

Far Cortical Locking

To address the concern that current locked plate constructs may be too stiff to permit adequate callus formation, Bottlang et al developed the concept of far cortical locking. Unlike standard locked screws, in which the screw achieves threaded purchase in both the near and far cortex, the far cortex locking screw has a smooth shaft with threads at the tip that achieve purchase in only the far cortex. The smooth shaft of this screw decreases the stiffness of the plating construct by acting as an elastic cantilever beam. Bending of these flexible screw shafts can occur with axial loading of the implant construct (Figure 7).

Greater callus was seen with far cortical locking implants compared to standard locked implants in a sheep tibial osteotomy study. At 9 weeks following fixation, the callus volume was 36% higher and the bone mineral content 44% higher in the animals treated with the far cortical locking implants. The callus formation in the standard locked implants was asymmetric with less bone mineral content in the medial callus. Mechanically, the specimens treated with the far locking implant were 54% stronger in torsion and sustained 156% greater energy to failure in torsion.

Dynamic Locking Screw

Döberle et al reported on the use of a dynamic locking screw, also designed to reduce the stiffness of locked plate constructs. This dynamic locking screw is composed of 2 elements: an outer sleeve with threads that engage the bone and an inner pin with threads that lock to the plate. The inner pin is designed in a way that allows movement within the outer sleeve, while the plate–screw interface and bone–screw interface remains constant.

In their mechanical study comparing the dynamic locking screw with a standard locked screw, they reported that the dynamic locking screws reduced the axial stiffness by 16%. The interfragmentary
motion at the near cortical side (adjacent to the plate) was significantly greater with the dynamic locking screw (423 μm) compared with the standard locked screw (282 μm).

CONCLUSION
Mechanical conditions at the fracture site, principally the fixation stability, influences callus formation during fracture healing. The position and number of locked screws influences the plate construct stiffness and the degree of interfragmentary motion at the fracture site. Locked plates, when applied without direct interfragmentary compression, function in a bridge plate mode that provides relative stability. Fracture healing in this situation will occur with callus formation through secondary or indirect fracture healing. When the fracture gap is too great or the amount of interfragmentary motion is too little, adequate callus formation cannot occur. Increasing the working length of the plate and decreasing the number of screws may reduce locked plate stiffness and increase interfragmentary motion, but only at the far cortex. Novel experimental implants, including far cortical locking screws and dynamic locking screws, have been shown to reduce the bending stiffness of locked plate constructs with the goal of optimizing callus formation and secondary fracture healing.

REFERENCES