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Why and how do locking plates fail?

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ABSTRACT

Locking plates have led to important changes in bone fracture management, allowing flexible biological fracture fixation based on the principle of an internal fixator. The technique has its indications and limitations. Most of the typical failure patterns arise from basic technical errors. Types of locking plates, material properties and the general principles of locking plate applications are reviewed together with their misapplication.

Evolution of locking plates

The biomechanical aspects affecting overall bone-plate construct stability incorporate such components as fracture stability, stress shielding, load-sharing between plate and bone, screw anchorage in the bone and stability of the implant itself. The latter characteristic depends on the design and material of the plate system as well as on the fracture morphology. The ultimate aim of each osteosynthesis is to create appropriate fracture stability and to maintain implant stability during the fracture healing process for uneventful bone healing.

The principle of meticulous anatomical reduction of each fracture fragment by direct fracture exposure [1] and subsequent fixation by compression plating, as practiced by surgeons through the 1980s, required extensive soft tissue intervention not respecting the biological environment and generating fragment devascularization with subsequent bone necrosis [2].

Although they are not mutually dependent, the introduction of locking plates coincided with development of minimally invasive approaches of fracture fixation, and has led to important changes in fracture management [2,3]. The biomechanical principles of locking plate fixation differ from non-locking plating, and these differences should be understood by surgeons. Non-locking plates rely on friction between bone and implant to counteract shear stresses created by loading. In contrast, by creating angle-stable fixation and functioning as a single-beam construct, locking plates convert shear stress created during loading to compressive stress at the screw-bone interface. Since bone has greater resistance to compressive than shear stress, fixation is improved. Further, in a locked plate construct, the overall fixation strength equals the sum of the holding strengths at all screw-bone interfaces, rather than being just equal to the holding strength of the frictional force generated by the screw compression as in unlocked plates [4,5].

Early versions of locking plates were the Zespol plate, the Schühli nut and the PC-Fix [2]. In parallel to the Arbeitsgemeinschaft für Osteosynthesefragen (AO), which introduced the locking compression plate (LCP) and the less invasive stabilization system (LISS) based on a conical double-threaded screw head that locks in the threaded plate hole [6,7], Sürer presented the Surfix system [8], where the screw head is locked by a threaded locknut, which is screwed into the plate on top of the screw head.

In contrast to non-locking plates, locking plates can be placed elevated from the bone surface without precise shaping of their undersurface, because their fixation does not require plate-to-bone compression, thus preventing damage to the periosteal blood flow caused by pressure of the plate [2]. Use of monocortical screws is also possible. Thus, locking plates can be used as an “internal fixator”, providing flexible biological fracture fixation avoiding direct exposure to the fracture zone [2]. Moreover, the fracture can be reduced indirectly and the plate can be placed through minimally invasive approaches – a procedure termed as minimally invasive plate osteosynthesis (MIPO) [9].

Types of locking plates

Apart from differences in plate dimension and plate design, two main types of locking plates exist. First, there are fixed-angle locking plates, where the locking screws have to be inserted in a predefined angle, usually orthogonal, relative to the plate. Fixed-angle locking screw applications require use of a drill sleeve correctly fixed in the threads of the plate hole to maintain the proper insertion angle [10]. The other type are the so-called variable-angle (polyaxial) locking plates, where locking screw insertion is possible in a certain cone-shaped corridor of angulation relative to the plate hole axis. In contrast to the fixed-angle solution, screw locking can be maintained

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at inclined orientations in those locking plates, however, often at the expense of reduced stability at the locking interface [11].

The locking interface design differs depending on the manufacturer of locking plates. Some specific characteristics are outlined as follows. In general, the interfaces of fixed-angle locking plates are considered more stable in comparison to those of polyaxial locking plates [11]. In contrast to the cone-shaped threaded head of the DePuy Synthes fixed-angle locking screw, the cup-shaped threaded head of their variable-angle (VA) locking screws allows screw head locking in an angled orientation [10]. The VariAX polyaxial locking system (Stryker) is based on a thread in circular lip connection [12]. The IXOS system with Smart-Drive polyaxial locking screws (KLS Martin) is based on a tight fit and frictional connection of the screw head in the plate using different materials [12]. The latter two locking technologies revealed equivalent locking strength in 5° and 10° inclination; however, their failure moment drops in the 0° orientation [10,12]. The Peri-Loc polyaxial locking system (Smith & Nephew) uses a star petal interface at the plate hole to allow polyaxial locking screw orientation [13]. The TriLock polyaxial locking system (Medartis) is based on a spherical three-point wedge locking with additional friction locking through radial bracing of the screw head [14]. The Non-Contact-Bridging (NCB) plate system (Zimmer) applies a principle comparable to the Surfix system described above, however, with a spherical screw head which is locked via frictional coupling in the plate hole by an endcap superimposed on top of the screw head [13,15].

The locking compression plate (DePuy Synthes) allows hybrid constructs with use of locking and non-locking screws at the same plate due to so-called combi-holes. Non-locking screws could be used to reduce the fracture indirectly via the plate by pulling it to the bone. In simple diaphyseal fractures, where compression has to be applied at the fracture gap to prevent nonunion [16], eccentric centrifugal insertion of the non-locking screws in the plate hole exerts additional compression at the fracture gap. Angular stability in such constructs could be achieved by subsequent additional locking screw placement in the remaining plate holes [16].

General principles and misapplications

Implant related failure

As reported by Stoffel et al., when locking screws are well-fixed in the bone, construct failure is not a result of an insufficient screw-bone interface contact, but of factors related to the locking plate itself [17].

Locking screw bridging the fracture gap

Most locking screws cannot exert compression, due to the head-locking mechanism in the plate hole. Insertion of a locking screw crossing the fracture line at the fracture gap should therefore be avoided, because in this position it acts as set screw. As a result, it stiffens the construct, stabilizes the fracture with a gap between the fragments, and blocks micromotion at the fracture site [18]. Fracture healing by callus formation is subsequently impeded and plate breakage induced.

Plate-bone distance

Although not strictly claimed, placing the locking plates close to the bone increases axial and torsional construct stability [17,19,20]. Fixing the locking plate at 5-mm elevation from the bone reduces the axial failure load by about one third in comparison to a locking plate placed flush or at a maximum of 2-mm distance to the bone [19]. Reduction clamps, conventional screws or the whirlybird push-pull device can be used to approach and position the locking plate close to the bone. The end-cap locking mechanism of NCB plates allows compression of the plate to the bone before end cap application. The rotation of the locking plate towards the bone is another important parameter influencing construct stability and locking-screw cutout resistance which will be discussed later.

Plate material, dimension and shape

Material, dimension and shape of the plate influence its stiffness. Locking plates are made of either stainless steel (e.g. 316L, Fe-18Cr-14Ni-2.5Mo) or titanium alloy (e.g. TAN, Ti-6Al-7N) [21]. Titanium plates (elastic modulus 100 GPa) are less stiff than stainless steel plates (elastic modulus 180–200 GPa) of the same dimension [17, 22]. The increased flexibility of titanium plates allows a higher initial mechanobiological fracture stimulation resulting in periosteal callus formation [22]. However, screw configuration and number of screws have a 2- to 4-fold higher influence on the mechanobiological fracture stimulation compared to the plate material [22]. A recent biomechanical study revealed a shorter fatigue life of titanium plates compared to stainless steel plates of the same dimension under alternating loads [20], although the fatigue endurance limit of both materials is in the same range (stainless steel 310–448 MPa, titanium alloy 379–448 MPa) [22]. Commercially pure titanium is known for its low corrosion rate and exceptionally good biological tolerance, however, its limited ductility surprised orthopedic trauma surgeons who were accustomed to the use of steel, which deforms markedly before breaking occurs [23].

Plate dimension is an important factor influencing construct stability in comminuted fractures with lacking cortical support. The most relevant measure of plate dimension is the cross-section of the plate bridging the fracture gap. Depending on fracture location and morphology, the correct plate dimension has to be chosen. If the plate is under-dimensioned in an open-gap situation, early plate failure will occur due to its overloading. The following applications will elucidate the problem in more detail. Attributed to a different plate design, the 4.5/5.0 distal femur VA locking plate revealed an earlier mechanical failure compared to the LISS and the 4.5/5.0 LCP in a case series of comminuted distal femur fractures [24]. Plate bending of this stainless steel VA plate occurred with metal breakage from the screw-hole tabs to the plate periphery. On the other hand, the LCP has its weakest point at the dynamic compression part of the combi-holes [16,17]. This is the location where plate breakage occurs (Fig. 1) [16]. The VA locking plate has four screw tabs at each screw hole. Due to an enlarged overall hole diameter comprising the tabs, the remaining cross-section of the plate at the VA screw hole level is further reduced compared to the dynamic compression part of the LCP combi-hole [24]. The screw threads and the tabs of the VA screw hole generate sharp edges where peak stress could occur and cyclic loading may result in crack initiation and propagation [17].

The reconstruction plate is a locking plate specially developed for contouring. Its design includes indentations at the lateral edges to facilitate contouring. Because of its susceptibility to bending forces, reconstruction plates should not be applied for long bone shaft fractures and clavicle shaft fractures where high bending forces and torsional moments exist. Breakage of the reconstruction plate is observed regularly in these locations (Fig. 2c).

LCPs correctly sized to the injured bone are more appropriate for this application. In tibia shaft fractures stabilization with a 3.5 LCP might be under-dimensioned, resulting in plate failure despite a correct working length (Fig. 2). In this anatomical region a 4.5/5.0 LCP should be applied.

In this context, it is advisable to use the broader double-row locking grid plates in comminuted phalangeal fractures instead of the weak single-row locking plates (Fig. 2b).

Plates with a larger cross-section [25] or orthogonal double plate osteosynthesis [26] stiffen the bone-implant construct. Stiffer plate