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Evolution of plate design and material composition

David J. Hak[a,*], Rodrigo Banegas[a], Kyros Ipaktchi[a], Cyril Mauffrey[a]

[a] Denver Health, University of Colorado, Denver, Colorado, USA

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ABSTRACT

The evolution of plate fixation of fracture was accompanied by advances in metallurgy and improvement in understanding of the requirements for successful fracture healing. Locked internal fixation minimizes biologic damage and when used in conjunction with minimally invasive approaches may optimize fracture healing. Some current metal locked plate constructs may actually be too stiff, and various methods including screw modification, plate hole modification, and changes in plate material composition may provide a solution to optimize fracture healing. This paper reviews the evolution of plate design and describes the early clinical experience with the use of carbon fibre reinforced reinforced polyetheretherketone composite plates.

Evolution of plate design

Open reduction and internal fixation using plates was popularized by the Arbeitsgemeinschaft fur Osteosynthesefragen (AO) group and gained widespread acceptance for the operative fixation of fractures and osteotomies. Their initial plate contained round screw holes and fracture site compression or axial loading was achieved using an external compression device. In 1965 the AO introduced the dynamic compression plate (DCP). The sides of the screw holes in this plate are inclined, and when a screw is inserted eccentrically into the hole, the screw head impacts the angled side causing movement of the plate leading to compression of the fracture.

Conventional open reduction and internal fixation usually requires wide surgical exposure to access and directly visualize the fracture. It requires pre-contouring of the plate to match the surface anatomy of the bone. Fixation stability with a conventional non-locked plate relies upon the force of friction between the plate and the bone (Fig. 1). Stability is dependent on achieving and maintaining an adequate frictional force, which can be challenging in osteoporotic bone or in situations where there is delayed healing. Loosening of screws, along with loss of adequate friction between the plate and bone, can lead to fixation failure and nonunion.

One disadvantage of conventional plate fixation is the damage to the periosteum beneath the plate. This initially produces necrosis beneath the plate and with time results in localized osteopenia [1]. Focus on minimizing the periosteal damage lead the AO to develop the Limited Contact-Dynamic Compression Plate, which was introduced in 1990, that has an undercut surface compared to the smooth surface of the original Dynamic Compression Plate [2]. Further decrease in the plate “foot print” was achieved with the Point Contact Fixator (PC-Fix) [3] (Fig. 2).

The PC-Fix, which was the forerunner of today’s locking plate implants, was designed for fixation of forearm fractures and has small points on the undersurface to limit the plate contact with bone [4]. The screws for this implant were self-tapping and designed to engage only the near cortex so are available in only one length. The screws, like todays locking implant screws, thread into the reciprocal threaded plate holes. The use of monocortical locking screws was continued with the introduction of the Less Invasive Stabilization System (LISS). The LISS plate, which is anatomically shaped, is designed for fixation of distal femur and proximal tibia fractures [5]. Further advancements lead to the development of the Locking Compression Plate (LCP) which was released for clinical application in March 2000 [6].

Locking plates use screws that have threads on the screw head that engage matching threads in the plate holes, creating a fixed angle implant. Stability is achieved by the engagement of the locking screws in the plate and does not rely on compression of the plate to the bone as in conventional plate fixation (Fig. 3). Locking plates offer several advantages over conventional non-locking plates including improved fixation in osteoporotic bone. Locked plates are commonly used in a “bridge plate” function, preserving periosteal and soft tissue blood supply and providing fixed angle stability. Unlike conventional non-locking plates they do not require exact plate contouring to match the bony contours since the plate does not need to sit directly on the bone surface [7]. The use of minimally invasive surgical techniques became popularized simultaneously with the widespread adoption of locking plating techniques [8].

Initially, locking screws were designed to be inserted along a set axis in order to properly engage the plate thread locking mechanism. Locking screws inserted off-axis in these systems showed a significant decrease of failure load [9]. Correct placement of fixed angle locking screws required the use of a drill sleeve correctly fixed

* Corresponding author at: Department of Orthopedic Surgery, Denver Health Medical Center, 777 Bannock Street, MC 0188, Denver, Colorado, USA
E-mail address: David.hak@dhha.org (David J. Hak).

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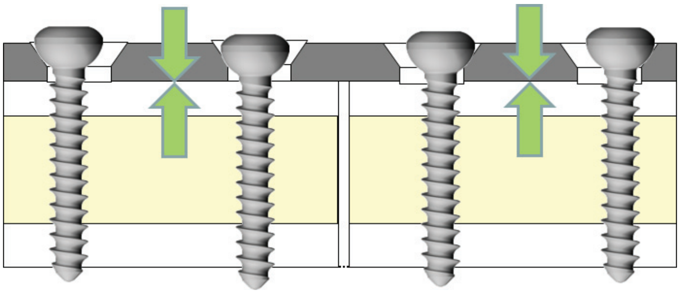

Fig. 1. Fixation stability with a conventional non-locked plate relies upon the force of friction (green arrows) between the plate and bone.

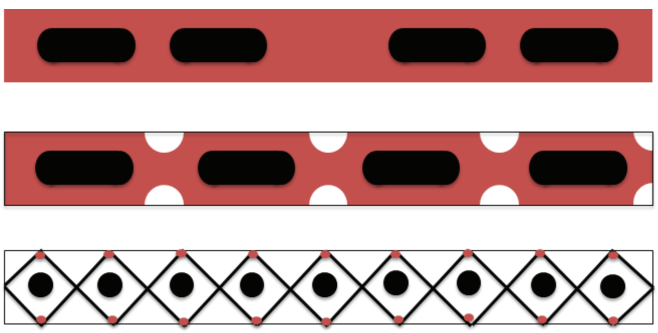

Fig. 2. Cortical contact area (red) of original AO dynamic compression plate (top), AO limited contact dynamic compression plate (middle), and point contact fixator (bottom).

in the threads of the plate hole. Without the proper use of the drill sleeve, the correct screw insertion angle could not be maintained. In certain complex fracture patterns, fragment specific fixation may require orientation of a screw different than that directed by a fixed locking screw axis. Manufacturers developed various alternative locking mechanisms, including newer plate designs that enable more options to strategically place the locking screws within a variable range of axes [10]. The different "polyaxial" locking interface designs that have been developed include those based on tight fit, and frictional connection or a thread in circular lip connection [11]. In general, these systems allow inclination of the screw insertion angle up to 15°, while maintaining a locking strength equivalent to fixed angle locking screws inserted with 0° inclination.

Metal plate composition

Metal has long been the foundation for orthopedic implants. Metal implants offer the benefits of high strength, high stiffness, ease of machining, and low cost. Additionally, many metals offer good ductility allowing them to be manually bent or contoured intra-operatively to fit individual fracture sites.

The use of stainless steel for surgical applications began in 1926 when Strauss patented 18Cr-8Ni stainless steel that contains 2–4% molybdenum and a very low percentage of carbon, having sufficient corrosion resistance for implantation in the human body [12]. Stainless steel became the most frequently used metal for internal fixation devices because of its favorable combination of mechanical properties, corrosion resistance and cost effectiveness compared to other metallic implant materials.

The AO group began exploring the use of pure titanium for plate fixation in the late 1960s. Commercially available pure titanium contains varying traces of iron, oxygen, nitrogen, carbon and hydrogen. There are different grades of pure titanium based on the amount of these trace elements, which influence its mechanical properties. In addition to pure titanium, titanium alloys are also used for internal fixation plates. Ti-6AI-4V contains a nominal

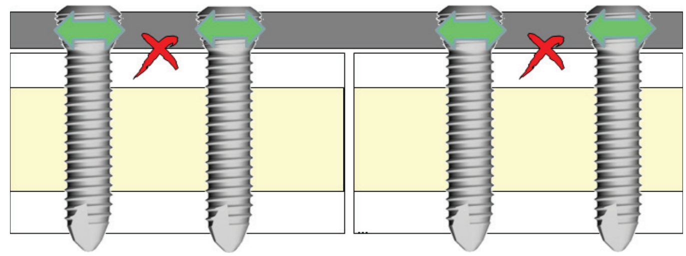

Fig. 3. Fixations stability with a locked plate is achieved by the engagement of the locking screws in the reciprocal threaded plate holes (green arrows) and there is no compression of the plate against bone.

6% aluminum and 4% vanadium. The addition of aluminum and vanadium to commercially pure titanium produces an alloy whose mechanical properties are closer to that of cold-worked stainless steel. Ti-6AL-7Nb which is an alloy containing 6% aluminum and 7% niobium was developed as an alternative to Ti-6AI-4V because of concerns that vanadium has demonstrated cytotoxic outcomes when isolated [13].

Titanium offers several advantages over stainless steel. Compared to stainless steel, titanium and titanium alloys better match the modulus of elasticity of bone. Titanium has greater superior strength under repeated load stresses, making it capable of withstanding higher strains during internal fixation. It is also considered more biocompatible, with excellent corrosion resistance and chemical inertness. The excellent corrosion resistance of titanium and titanium alloys is due to the formation of an adhesive TiO_2 oxide layer on their surface. One disadvantage of titanium fracture fixation plates is the problem of cold-welding seen with the removal of locking screw constructs [14,15].

Disadvantages of metal plates

Advances in metallurgy, including addition of various surface coatings, have been beneficial in improving orthopedic care. However, disadvantages of metal implants include a limited fatigue life, mismatch of modulus of elasticity with bone leading to stress shielding, potential for generation of wear debris, corrosion, and their radiodensity that can preclude accurate radiographic visualization.

While stiff metal plates worked well for direct fracture reductions in which the load was shared by bone, they may not be optimal for certain cases of indirect reduction with relative stability in which you want more flexible fixation to stimulate callus formation. A 20% rate of nonunion was reported in a retrospective review of 86 distal femur fractures treated with locked metal plate fixation. Limited callus formation in these cases suggest that mechanical factors may play a role in the failure of fracture healing [16].

Several strategies to reduce the stiffness of locked-plate constructs have been proposed. One strategy is that of far cortical locking in which locking screws that engage the far cortex of bone have a reduced mid-shaft diameter to bypass the near cortex, allowing for elastic cantilever bending of the screw shaft within the near cortex [17]. A prospective and observational study of 32 consecutive patients with 33 distal femur fractures treated by plate fixation with far cortical locking screws were followed up for a minimum of 1 year with functional and radiographic assessments [18]. Thirty-one fractures were available for follow-up. Thirty of the 31 fractures healed at an average of 15.6 weeks. There were no cases of hardware failure. Two patients underwent revision surgery, one to correct a malrotation at day 5 and one to treat a nonunion at 6 months. The investigators concluded that the absence of implant and fixation failure suggests that dynamic plating of distal femur fractures with far cortical locking screws provides safe and effective fixation.