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Pre-operative planning for fracture fixation using locking plates: device configuration and other considerations

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KEYWORDS

Screw
Bone
Working length
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Interfragmentary motion

ABSTRACT

Most locked plating failures are due to inappropriate device configuration for the fracture pattern. Several studies cite screw positioning variables such as the number and spacing of screws as responsible for occurrences of locking plate breakage, screw loosening, and peri-prosthetic re-fracture. It is also widely accepted that inappropriate device stiffness can inhibit or delay healing. Careful preoperative planning is therefore critical if these failures are to be prevented. This study examines several variables which need to be considered when optimising a locking plate fixation device for fracture treatment including: material selection; screw placement; the effect of the fracture pattern; and the bone-plate offset. We demonstrate that device selection is not straight-forward as many of the variables influence one-another and an identically configured device can perform very differently depending upon the fracture pattern. Finally, we summarise the influence of some of the key parameters and the influence this can have on the fracture healing environment and the stresses within the plate in a flowchart.

Introduction

Preoperative planning is critical to the success of any fracture fixation surgery. For any fixation device there are three key clinical requirements and consequent mechanical demands arising from them [1]: it must support fracture healing; it must not fail during the healing period; and it should not loosen or cause patient discomfort.

It is well recognised that an appropriate amount of interfragmentary motion (IFM) between fractured bone fragments is pivotal to healing; too much or too little can delay or inhibit fracture healing [2]. IFM is determined by the stiffness of the bone-fixator construct with stiffness defined as IFM produced on application of unit load. Moreover, to prevent failure, stresses within the implants should not be too high. Fatigue is normally a more likely cause of failure rather than a single traumatic event and the implant is more prone to fatigue failure if healing has been delayed [3]. Small increases in stress can, therefore, reduce significantly the number of cycles to failure of the fixation device [4]. High strains/stresses at the screw-bone interface are known to cause loosening around screw holes and entail a risk of infection [5,6]. In addition, compromising the integrity of the bone due to screw holes or bone atrophy can lead to periprosthetic fracture during fixation or re-fracture after device removal [7].

In the context of metallic plates for fracture healing, preoperative planning must consider the different plate types available. The benefits of locking plates have been demonstrated clinically and experimentally [8,9]. Several studies show that the use of locking screws can improve construct strength [10–12] and performance in osteoporotic bone compared to conventional screws [13–15]. On the other hand, studies have also shown that the pull-out strength of conventional screws increases with bone density [16,17] which can result in equivalent or even better results than locked plating in healthy bone [14]. These differences arise due to two main factors: (1) The preloads involved in compression screw tightening increase strain levels at the screw–bone interface even before physiological loads are applied, whereas locking screws have negligible screw-tightening preload and resulting strains [13,18]; and (2) During physiological loading, compression plating allows for frictional load transfer at the plate–bone interface; locked plating, on the other hand, transfers all physiological loads via the screw–bone interface [18]. In particular, the localised high tensile strains produced by conventional screws have been shown to be responsible for their poorer performance in osteoporotic bone [18]. Therefore, there should be a very clear distinction made between these two screw types; indeed, locking screws are not really screws in the conventional sense – they are more like bolts [19]. For example, the use of conventional screws can help reduce the fracture during surgery; on the other hand, once a locking screw has been inserted, it prevents further distraction or reduction of the fracture [20].

It is well accepted that the majority of locked plating failures are due to inappropriate device configuration for the fracture pattern

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0020-1383/

[21–25]. Several studies cite screw positioning variables such as the number and spacing of screws as responsible for cases of locking plate breakage, screw loosening, and periprosthetic re-fracture [3,8,26–29]. However, the significance of different variables and manner in which their variation affects mechanical behaviour of fixation constructs (and associated clinical expectations) is poorly understood; many of the findings in this respect are contradictory. To achieve the clinical requirements, a well-planned device selection and configuration is essential, which in turn requires understanding the influence of different variables on the mechanical behaviour of bone-plate construct.

This aim of this study is to examine the role of different variables that influence pre-operative planning with a particular emphasis on device configuration, which is a key determinant for ensuring that the clinical requirements are met.

Philosophy of fixation

The decision whether to aim to for promotion of primary (direct) or secondary (indirect) bone healing needs to be made before any fixation device selection. Delayed fracture healing or non-union is very likely to occur when the fracture environment is not controlled to achieve one of these fixation philosophies [30]. Secondary bone fracture healing is the most common form of healing and the surgery required is less invasive and biologically damaging [2,31]. To stimulate secondary bone healing, the initial post-operative interfragmentary movement (IFM) should be in the region of 10–40% of the total fracture gap [32,33]. As the interfragmentary strain governs the healing process, the smaller the size of the fracture gap, the smaller the required movement. The appropriate value of IFM and resulting interfragmentary strain changes throughout the course of healing [34]. Primary bone healing is a much slower process requiring so-called 'absolute stability' of the fracture, and therefore aims to completely abolish the fracture gap; consequently, the required IFM tends to zero [34]. If any significant movement occurs in a small fracture gap, this results in very large strains and is disruptive to healing. Conversely, it is almost impossible to abolish relative movement between fracture fragments in a severely comminuted fracture pattern and therefore indirect bone healing should be sought [35]. Clinical studies demonstrate that using a lag screw to abolish movement in this situation conflicts with the goal of indirect healing leading to hardware failure [8]. One of the criticisms of locking plates is that the final bone-plate construct can become overly stiff thereby delaying or preventing healing [20]. Therefore, the stiffness of the device should be carefully controlled.

Implant material selection

The interfragmentary movement (IFM) at the fracture site is largely governed by plate bending [36], and consequently plate stiffness needs to be carefully controlled to avoid it from being too high or too low and thereby detrimental to healing. Material choice is known to influence healing rates in distal femur locking plates, particularly in the period up to 12 weeks post-operative [37]. It is intuitive that titanium, with a lower Young's modulus than steel, produces greater interfragmentary movement (IFM). However, the increase in IFM produced by titanium compared to steel is not proportional to the difference in material stiffness as the plate is eccentric to the applied load [38]. The geometry of the plate, particularly the structural bending stiffness, also influences the IFM in a similar manner to the material stiffness.

Any implant will alter the natural load distribution within the host bone. Fixation devices are designed to redirect load and shield the bone from undesirable motion to allow the fracture to heal [39]. This redirection of load also results in other unwanted effects: for example, stress-shielding in some regions and strain concentration at the bone-implant interface. In locking plates, it has been shown that a more rigid screw material (e.g. steel with a higher Young's modulus than titanium) reduces the strain concentrations at the screw-bone interface [36] since they deform less in bending. The same applies to the stiffness of the plate itself – higher stiffness plates reduce screw-bone interface strain concentrations [36]. As material failure of bone and consequent loosening of screws is governed by strains, their concentration at the bone-screw interface needs to be limited. The concern of high interfacial strains with titanium in comparison to steel has been previously noted for unilateral fixators [40].

Device configuration: working length

One of the most important parameters regulating the device stiffness is the working length (also known as the bridging span), defined as the distance between the two innermost screws on either side of the fracture. Small working lengths in a simple reduced fracture can cause large plate stresses [4,24,41]; but in comminuted fracture patterns with a fracture gap, it is large working lengths that result in higher plate stresses [9]. This apparent contradiction has led to some confusion in the literature regarding the influence of working length. Bottlang et al. [42], for example, noted that the efficacy of working length, in terms of stiffness reduction, is "inconsistent and is gained at the cost of construct strength". The mechanics for the two cases, one with a fracture gap and the other little or no fracture gap, can be explained as follows: When there is a fracture gap, the entire load is transmitted from one bone fragment to the other via the plate. In this case, upon load bearing, a higher working length results in flexible system leading to increased bending, higher plate stresses, higher interfacial bone strains and higher IFM. However, when there is no fracture gap the loads are shared between the bone and the plate. In this case a more flexible plating system (e.g. due to a larger working length) results in a lower load being transferred via the plate resulting in lower plate stresses and lower interfacial strains.

Unfortunately, the distinction between the performance of load-bearing and load-sharing locked plating systems is not fully understood. For example, some studies have attributed insufficient working length to higher plate stresses even for cases with a fracture gap [13,19,20]. This is explained [19] by applying identical angular deformation to the plate – a scenario in which a smaller working length will result in larger plate stresses.

A comparison between identical angular deformations with different working lengths is not clinically relevant, however, as plate stresses develop due to the identical loads (and not identical deformations) that the plate supports during weight-bearing. For a system with a large fracture gap, identical loads will cause larger plate stresses in a system with a larger working length (Fig. 1a). This is due to the lower stiffness of the longer working length which results in larger deformations and plate strains. In some cases, when the fracture gap is small, interfragmentary contact can occur between fracture fragments [43]. If this happens, then the bone transmits load and the plate is shielded from stress increases as shown in Fig. 1b [41,43]. This is a load-sharing situation. In fracture patterns with wider gaps or comminution, interfragmentary contact cannot occur and the plate will have to transmit the full weight-bearing loads.

This means that an identically configured device can perform very differently depending upon the fracture pattern. For example, using three identical screw configurations, Stoffel et al. [41] found that larger working lengths produced the lowest plate stresses for small fracture gaps (1 mm), but the highest plate stresses for larger fracture gaps (6 mm). A flexible plate will deform more than a rigid plate under identical loading, developing larger strains in a load-bearing situation, but allowing load-sharing to occur and relieving strains if interfragmentary contact can occur.