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1.2 Biology and biomechanics in bone healing

The biological and biomechanical basis of fracture management will be dealt with in this chapter. We will review how fractured bone behaves in different biological and mechanical environments and how this will influence the choice and method of treatment by the surgeon. Any surgical procedure may alter the biological environment and any fracture fixation will alter the mechanical environment. These changes may have a profound effect on fracture healing and are determined by the surgeon, not the patient. Thus, it is essential that all trauma surgeons have a basic knowledge of the biology and biomechanics of fracture healing so they can make wise decisions in fracture management (Tab 1.2-1). This chapter offers a review for the active clinician rather than a pure scientific analysis. In spite of worldwide research, much remains unknown or controversial in this rapidly changing scientific field.

The main goal of internal fixation is to achieve prompt and, if possible, full function of the injured limb. Although reliable fracture healing is only one element in functional recovery, its mechanics, biomechanics, and biology are essential for a good outcome. Fracture fixation is always a compromise: For biological or biomechanical reasons it is often necessary to sacrifice some strength and stiffness of fixation and the optimal implant is not necessarily the strongest or the stiffest available.

- It is not the purpose of osteosynthesis to permanently replace a broken bone but to provide temporary support to allow early functional rehabilitation with healing in a proper anatomical position.

Under critical conditions, the mechanical requirements may gain precedence over biological demands and vice versa. Similarly, the choice of implant material is a trade-off, eg, the mechanical strength and ductility of steel versus the electro-chemical and biological inertness of titanium. The surgeon determines which combination of technology and procedure best fits his experience, environment, and, in particular, the demands of the patient.

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Tab 1.2-1 The relationship between fracture type, stability of fixation, and fracture healing.
2 Characteristics of bone

Bone serves as a scaffold that supports and protects soft structures and enables locomotion and mechanical functioning of the limbs.

- The important mechanical characteristics of bone are its stiffness (bone deforms only little under load) and strength (bone tolerates high load without failure).

In considering a fracture and fracture healing, the brittleness of bone is of special interest: Bone is a strong material, but it breaks under very small deformation. This means that bone behaves more like glass than like rubber. Therefore, at the onset of natural fracture healing, bone cannot bridge a fracture gap which is repeatedly subject to displacement. For an unstable or flexibly fixed fracture (relative stability), a sequence of biological events—mainly the formation of first a soft and then a hard callus—helps to reduce the strain and deformation of the repair tissues (chapter 1.2:4.3.3). Resorption at the fracture ends increases the fracture gap. The repair tissue is less stiff and this combination reduces the strain at the fracture site. A lower-strain environment promotes the formation of bridging callus which increases the mechanical stability of the fracture. Once the fracture is solidly bridged, full function is restored. Internal remodeling then restores the original bone structure, a process which takes years.

3 Fracture of bone

A fracture is the result of single or repetitive overload. The fracture occurs within a fraction of a millisecond. It results in predictable damage to soft tissues due to rupture and an implosion-like process. Rapid separation of fracture surfaces creates a void (cavitation) and results in severe soft-tissue damage (Video 1.2-1).

3.1 Mechanical and biochemical effects

A fracture produces a loss of bone continuity that results in pathological deformation, loss of the support function of bone, and pain. Surgical stabilization may restore function immediately and alleviate pain. Thus, the patient regains pain-free mobility and avoids such sequelae as complex regional pain syndromes (chapter 4.7).

Fracture of bone ruptures blood vessels within bone and periosteum. Spontaneously released biochemical agents (factors) help to induce bone healing. In fresh fractures these agents are very effective and scarcely need any boost. The role of surgery should be to guide and support this healing process.

Video 1.2-1 Implosion of a bone during fracture.
3.2 Fracture and blood supply

Although a fracture is a purely mechanical process, it triggers biological reactions such as bone (callus) formation and bone resorption. These two processes depend on an intact blood supply. The following factors influence blood supply at the fracture site, and have an immediate bearing on the surgical procedure:

- Mechanism of injury: The amount, direction, and concentration of forces at the fracture site will determine the fracture type and associated soft-tissue injuries. As a result of the displacement of fragments, periosteal and endosteal blood vessels rupture and the periosteum is stripped. Cavitation and implosion of the fracture cause additional soft-tissue damage.
- Initial patient management: If rescue and transportation take place without splinting of fractures, motion at the fracture site will add to the initial damage.
- Patient recuscitation: Hypovolemia and hypoxia will increase damage to injured soft tissues and bone and must be corrected early in patient management.
- Surgical approach: Surgical exposure of the fracture will invariably result in additional damage [1]. This can be minimized by having a thorough knowledge of anatomy, careful preoperative planning, and meticulous surgical technique.
- Implant: Considerable damage to bone circulation may result not only from the surgical trauma, but also from the contact between implant and bone [2]. Plates with a flat undersurface (eg, DCP) have a large area of contact; the LC-DCP, which is undercut, therefore was designed to reduce this contact area [3]. However, the extent of the contact also depends upon the relationship of the radii of curvature of the plate and the bone. When the radius of curvature of the undersurface of the plate is larger than that of the bone, plate contact may be in a single line, and this reduces the advantages of the LC-DCP when compared to the flat undersurface of the DCP (Fig 1.2-1a). If the situation is reversed and the plate has a smaller radius of curvature than the bone, there will be contact at both edges (two-line contact), and the lateral undercuts of the LC-DCP will significantly reduce the area of contact (Fig 1.2-1b–c).
- Consequences of trauma: Elevated intraarticular pressure reduces the epiphyseal bone circulation, especially in young patients. The increase in hydraulic pressure (produced by an intracapsular hematoma) has been shown to reduce blood supply to the epiphyseal bone, when the growth plate is still open.

![Fig 1.2-1a–c Area of contact under the plate.](image)

a If the radius of curvature of the undersurface of the plate is greater than that of the bone, a single line of contact will result. In this situation, the DCP and LC-DCP will have similar areas of contact.

b If the radius of curvature of the undersurface of the plate is smaller than that of the bone, the plate will have contact at both edges, producing a double-line contact.

c With contact only at the edge of the plate, the undercut underside of the LC-DCP reduces the area of contact.
Dead bone can only be revitalized by removal and replacement (creeping substitution through osteonal or lamellar remodeling), a process which takes a long time to complete. It is generally accepted that necrotic tissue (especially bone) predisposes to infection and sustains it (chapter 5.3). Another effect of necrosis is the induction of internal (Haversian) remodeling. This allows replacement of dead osteocytes but results in temporary weakening of the bone due to transient porosis, which is an integral part of the remodeling process. This is often seen immediately beneath plates and can be lessened by reducing the contact area of the plate (eg, LC-DCP), which maximizes the periosteal blood supply and reduces the volume of avascular bone.

An immediate reduction of bone blood flow has been observed after fracture or osteotomy, with the cortical circulation in the injured parts of the bone being reduced by nearly 50% [4]. This reduction has been attributed to a physiological vasoconstriction in both the periosteal and the medullary vessels as a response to trauma [5]. During repair of a fracture, however, there is increasing hyperemia in the adjacent intraosseus and extraosseous circulation, reaching a peak after 2 weeks. Thereafter, blood flow in the callus area gradually decreases again. There is also a temporary reversal of the normal centripetal blood flow after disruption of the medullary system.

- Microangiographic studies [6, 7] have demonstrated that much of the vascular supply to the callus area is derived from the surrounding soft tissues (Fig 1.2-2), a good reason not to strip any soft tissues!

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**Fig 1.2-2a–b** The blood supply of callus.

- **a** Before bony bridging.
  1. Nutrient artery ascending.
  2. Nutrient artery descending.
  3. Metaphyseal arteries.
  4. Periosteal arteries.

- **b** After bony bridging.
1.2 Biology and biomechanics in bone healing

Perfusion of callus is of utmost importance and may determine the outcome of healing. Bone can only form when supported by a vascular network and cartilage will not persist in the absence of sufficient perfusion. However, this angiogenic response depends upon both the method of treatment and the induced mechanical conditions:

- Vascular response appears to be greater after more flexible fixation, perhaps due to a larger volume of callus.
- Large strain in tissue, caused by instability, reduces the blood supply, especially in the fracture gap [8].
- The operative procedure during internal fixation of fractures alters the hematoma and soft-tissue blood supply. Following considerable intramedullary reaming, endosteal blood flow is reduced, but there is a rapid hyperemic response if reaming has been moderate.
- Reaming for intramedullary nails results in a delayed return of cortical perfusion, depending on the extent of reaming [9–11]. Reaming does not affect perfusion within the fracture callus, as blood supply to the callus is mostly from the surrounding soft tissues [12].
- In addition to the wider exposure of the bone, larger implant-bone contact will result in a reduction of bone perfusion, as bone receives its blood supply through the periosteal and endosteal lining.
- Damage to the blood supply is minimized by: avoiding direct fragment manipulation, minimally invasive surgery, and the use of external or internal fixators [13–16].

3.3 Biology of fracture healing

Fracture healing can be divided into two types:

- primary or direct healing by internal remodeling;
- secondary or indirect healing by callus formation.

The former occurs only with absolute stability and is a biological process of osteonal bone remodeling (chapter 1.2:4.4). The latter occurs with relative stability (flexible fixation methods). It is very similar to the process of embryological bone development and includes both intramembranous and endochondral bone formation. In diaphyseal fractures, it is characterized by the formation of callus.

Bone healing can be divided into four stages:

- inflammation;
- soft callus formation;
- hard callus formation;
- remodeling.

Although the stages have distinct characteristics, there is a seamless transition from one stage to another; they are determined arbitrarily and have been described with some variation.

Inflammation

After fracture, the inflammatory process starts rapidly and lasts until fibrous tissue, cartilage, or bone formation begins (1–7 days postfracture). Initially, there is hematoma formation and inflammatory exudation from ruptured blood vessels (Fig 1.2-3a). Bone necrosis is seen at the ends of the fracture fragments. Injury to the soft tissues and degranulation of platelets results in the release of powerful cytokines that produce a typical inflammatory response, ie, vasodilatation and hyperemia, migration and proliferation of polymorphonuclear neutrophils, macrophages, etc. Within the hematoma, there is a network of fibrin and reticulin fibrils; collagen fibrils are also present. The fracture hematoma is gradually replaced by granulation tissue. Osteoclasts in this environment remove necrotic bone at the fragment ends.

Soft callus formation

Eventually, pain and swelling decrease and soft callus is formed (Fig 1.2-3b). This corresponds roughly to the time when the fragments are no longer moving freely, approximately 2–3 weeks postfracture.
At the end of soft callus formation, stability is adequate to prevent shortening, although angulation at the fracture site may still occur.

The soft callus stage is characterized by the growth of callus. The progenitor cells in the cambial layer of the periosteum and endosteum are stimulated to become osteoblasts. Intramembranous, appositional bone growth starts on these surfaces away from the fracture gap, forming a cuff of woven bone periosteally, and filling the intramedullary canal. Ingrowth of capillaries into the callus and increased vascularity follows. Closer to the fracture gap, mesenchymal progenitor cells proliferate and migrate through the callus, differentiating into fibroblasts or chondrocytes, each producing their characteristic extracellular matrix and slowly replacing the hematoma [17].

**Hard callus formation**

When the fracture ends are linked together by soft callus, the hard callus stage starts (Fig 1.2-3c) and lasts until the fragments are firmly united by new bone (3–4 months). As intramembranous bone formation continues, the soft tissue within the gap undergoes endochondral ossification and the callus is converted into rigid calcified tissue (woven bone). Bone callus growth begins at the periphery of the fracture site, where the strain is lowest. The production of this bone reduces the strain more centrally, which in turn forms bony callus. Thus, hard callus formation starts peripherally and progressively moves towards the center of the fracture and the fracture gap. The initial bony bridge is formed externally or within the medullary canal, away from the original cortex. Then, by endochondral ossification, the soft tissue in the gap is replaced by woven bone that eventually joins the original cortex.

**Remodeling**

The remodeling stage (Fig 1.2-3d) begins once the fracture has solidly united with woven bone. The woven bone is then slowly replaced by lamellar bone through surface erosion and osteonal remodeling. This process may take anything from a few months to several years. It lasts until the bone has completely returned to its original morphology, including restoration of the medullary canal.

**Differences in healing between cortical and cancellous bone**

As opposed to secondary healing in cortical bone, healing in cancellous bone occurs without the formation of significant external callus. After the inflammatory stage, bone formation is dominated by intramembranous ossification. This has been attributed to the tremendous angiogenic potential of trabecular bone as well as the fixation used for metaphyseal fractures, which is often more stable. In unusual cases with substantial interfragmentary motion, intermediary soft tissue may form in the gap, but this is usually fibrous tissue, which is soon replaced by bone.
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Fig 1.2-3a–d  Stages of secondary bone healing.

a  The inflammation stage. Formation of hematoma resolving into granulation tissue with the typical inflammatory cascade.

b  The soft callus stage. Intramembraneous ossification forming bone cuffs away from the fracture gap. Replacement of the granulation tissue elsewhere in the callus by fibrous tissue and cartilage, and ingrowth of vessels into the calcified callus. This starts at the periphery and moves towards the center.
**Fig 1.2-3a–d (cont) Stages of secondary bone healing.**

- **c** The hard callus stage. Complete conversion of callus into calcified tissue through intramembraneous and enchondral ossification.
- **d** The remodeling stage. Conversion of woven bone into lamellar bone through surface erosion and osteonal remodeling.
4 Biomechanics and bone healing

4.1 Methods of fracture stabilization

The term stability is widely used by surgeons. Its meaning, though, differs from that used in engineering. The surgeon uses the word stability to express the degree of displacement at the fracture site induced by load.

- A stable fracture is defined as a fracture that does not visibly displace under physiological load.
- Fracture fixation with absolute stability means that there is no micromotion at the fracture site under physiological load.
- The degree of stability determines the type of fracture healing.

Fracture of a bone often produces an unstable situation. Obvious exceptions are impaction fractures of the metaphysis, nondisplaced fractures with intact periosteum, abduction fractures of the proximal end of the femoral neck, and greenstick fractures. These fractures do not require reduction, and stabilization is only required if the fracture will deform under physiological load.

The aim of fracture stabilization, in order of priority, is to
- maintain the achieved reduction;
- restore stiffness at the fracture site (thus allowing function);
- minimize pain related to instability at the fracture site.

- Fixation with absolute stability aims to provide a mechanically neutral environment for fracture healing, i.e., no motion at the fracture site. However, this also reduces the mechanical stimulus for repair by callus formation.

- Fixation with relative stability aims to maintain the reduction and still keep the mechanical stimulation for fracture repair by callus formation.

The prerequisite for successful relative stabilization is that the displacement occurring under load is elastic, i.e., reversible and not permanent. Fortunately, fracture healing by callus formation can take place within a wide spectrum of mechanical environments. If titanium elastic nails are compared to bridge plating using a locked plate, there is a large difference in the degree of micromotion at the fracture site. However, both will result in callus formation and fracture healing, if correctly applied.

At either end of the spectrum of relative stability, fracture healing will be delayed. Callus will not form if there is no motion, but if there is extensive movement and the fracture is unstable, healing will also be delayed.

4.2 Nonoperative fracture management

4.2.1 Fracture healing without treatment

Without treatment, nature stabilizes mobile fragments by pain-induced contraction of the surrounding muscles, which may lead to shortening and malunion. At the same time, hematoma and swelling increase—although temporarily—the tissue turgor and have a slight stabilizing effect. Observations made of bone healing without any treatment help to understand the positive and negative effects of medical intervention. It is surprising how initial mobility is compatible with solid bone healing (Fig 1.2-4). In such cases, the residual problem is lack of alignment and impairment of function.

4.2.2 Conservative treatment of fractures

Conservative management requires closed reduction to restore alignment. Subsequent stabilization maintains reduction and reduces mobility of the fragments, while indirect healing
occurs by callus formation. In conservative treatment, stabilization is achieved by the following means:

- **Traction:** This can be supplied via the skin or a metal pin inserted into the bone distal to the fracture (skeletal traction). Traction (Fig 1.2-5) along the long axis of the bone aligns the bone fragments by ligamentotaxis, and reduces motion, providing some stability.

- **External splinting:** Application of externally applied splints—made of wood, plastic, or plaster—results in a certain amount of fracture stabilization. The splint dimensions are the most important mechanical element. Circular external splints are very stiff and strong, based on their curved geometry. However, fixation with external splints

![Fig 1.2-4a–b](image1) Spontaneous healing of a femoral fracture of a Vietnam war victim.

- **a** AP x-ray.
- **b** Lateral x-ray.

![Fig 1.2-5a–c](image2) Fracture reduction and stabilization by means of traction.

- **a–b** The figures illustrate that the force reducing the fracture perpendicularly to the long axis decreases with alignment. Thus, gross mobility is reduced, while micromotion persists.

- **c** Stabilization of a fracture using a plaster cast. The plaster cast acts like a splint and the pressure of the soft tissues maintains alignment. This reduces mobility but does not prevent it. The cast represents a very stiff splint. Mobility occurs because the plaster cast can only be loosely coupled to the bone by soft tissues. If the plaster is too tight, compartment syndrome will occur.
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is inherently unstable because of poor coupling to bone caused by the interposed soft tissue. Externally applied splints maintain reduction by achieving three-point contact.

- A curved plaster cast produces a straight bone, a straight plaster cast produces a bent bone!

The pressure of the surrounding tissues reduces the movement of the fragments. In diaphyseal fractures, correct fragment length, alignment, and rotation are all that is needed for proper function of the limb. In articular fractures precise anatomical reduction is important to avoid joint incongruity or instability, which may lead to secondary arthrosis (chapter 2.3).

4.3 Surgical fixation with relative stability

4.3.1 Mechanics of techniques of relative stability

With relative stability, the bone fragments displace in relation to each other when physiological load is applied across the fracture. Displacement increases with the applied load and decreases with the rigidity of the fixation device. There is no exact definition of the required or tolerated flexibility. In general, a fixation method is considered flexible if it allows controlled interfragmentary movement under physiological load. Therefore, all fixation methods with the exception of compression techniques may be seen as flexible fixations that provide relative stability.

4.3.2 Implants

Devices such as external fixators, intramedullary nails, or internal fixators provide relative stability. The degree of flexibility can be varied and this is determined by how the surgeon applies the device and how it is loaded. All of these devices allow interfragmentary movement, which can stimulate callus formation. However, incorrect application of the device can result in excessive movement and inhibit bone union.

External fixators

External fixators usually provide relative stability, although some ring fixators can be used to apply compression and absolute stability. Unilateral external fixators are eccentrically located, and exhibit asymmetrical mechanical behaviour. They are stiffer when loaded in the plane of the Schanz screw than in the plane perpendicular to them. Ring fixators display almost uniform behaviour in all planes, so that displacement of the bone fragments in relation to each other is mainly axial.

The stiffness of fracture stabilization by external fixation depends on a number of factors, including

- the type of implants used, eg, Schanz screws and bars;
- the geometrical arrangements of these elements in relation to each other and the bone, ie, uniplanar, biplanar, or circular fixators;
- the coupling of the implant to the bone, eg, Schanz screws; tensioned fine wires.

The most important factors influencing the stability of fixation are:

- the stiffness of the connecting rods;
- the distance between the rods and the bone axis; the stiffer the rod and the closer it is to the bone axis, the more stable the fixation is;
- the number, spacing, and diameter of the Schanz screws or of the wires, and their tension.

The interfragmentary movement of a fracture with a unilateral external fixator under load is a combination of axial, bending, and shearing displacement. A double-tube arrangement under partial loading of 200–400 N results in interfragmentary movement of several millimeters and stimulates callus formation. The external fixator is the only system which allows the surgeon to control flexibility of the fixation by adjusting the implant without additional surgery. This technique, termed dynamization, may be used to modify the
loading of the fracture as healing progresses. This can be done by extending the distance between the rods and the bone, or by reducing the number of rods. In addition, some types of external fixators allow axial telescoping, to stimulate the healing process.

**Intramedullary nails**
The classical Kuntscher nail achieves good stability against bending moments and shear forces perpendicular to its long axis, but is rather unstable when torque is applied, and is unable to prevent axial shortening (telescoping). The torsional stiffness of slotted nails is low and the torsional and axial coupling between the intramedullary nail and the bone is loose. Therefore, in the past, the effective application of this intramedullary nail was confined to simple transverse or short oblique fractures, which cannot shorten and will interdigitate to prevent rotation. The advantage of the Kuntscher nail is that its flexibility promotes callus formation.

The introduction of locked intramedullary nails and solid or cannulated nails has overcome many of these restrictions. Locked nails withstand torsional moments and axial loading better [18]. The stability under these loads is dependent on the diameter of the nail, the geometry, and the number of interlocking screws and their spatial arrangement. The bending flexibility depends on the fit of the nail within the medullary canal and the extent of the fracture.

The only drawback of locked intramedullary nails is the non-linear stiffness of the nail-bone construction. The locking holes are larger than the diameter of the interlocking screws—this is to facilitate insertion by “freehand technique”. This allows some motion at the coupling, even at low loads. It may be decreased by insertion of further interlocking screws or by the use of angular-stable locking systems such as the expert tibial nail.

**Internal fixators and bridging plates**
Plates which span a multifragmentary fracture in the manner of an external fixator provide elastic splinting. The stiffness of such an internal fixation method depends on the dimensions of the implant, the number and position of the screws, the quality of the coupling between the screw and the plate, and the coupling between the screw and the bone. This will be influenced by plate design, (eg, locking head screws), the type of bone (eg, cortical versus cancellous), and the degree of osteoporosis. The mechanics of this type of fixation is discussed in detail in the chapters on bridge plating (chapter 3.3.2) and internal fixators (chapter 3.3.4).

- Plating with relative stability should only be applied in multifragmentary fractures and must not be used for simple fracture configurations as there is a high incidence of delayed union or nonunion. If simple (eg, metaphyseal) fractures are plated, a technique providing absolute stability must be used.

**4.3.3 Mechanobiology of indirect or secondary fracture healing**
Interfragmentary movement stimulates the formation of a callus and accelerates healing [19–21]. As the callus matures, it becomes stiffer, reducing the interfragmentary movement sufficiently, so that bridging by hard bony callus can occur (Fig 1.2-6). In the early stage of healing, when mainly soft tissue is present, the fracture tolerates a greater deformation or higher tissue strain than in a later stage when the callus contains mainly calcified tissue. The manner in which mechanical factors influence fracture healing is explained by Perren’s strain theory (Fig | Animation 1.2-7). Strain is the deformation of a material (eg, granulation tissue within a gap) when a given force is applied. Normal strain is the change in length (Δ l) in comparison to original length (l) when a given load is applied. Thus, it has no dimensions and is often expressed as a percent-
1.2 Biology and biomechanics in bone healing

Fig 1.2-6 Typical course of interfragmentary movement monitored for human tibial shaft fractures. The initial postoperative interfragmentary movements under 300 N axial load (normalized to 100% at the outset) decrease with the passage of time. After about 13 weeks, healing by callus has stabilized the fracture.

Age. The amount of deformation that a tissue can tolerate and still function varies greatly. Intact bone has a normal strain tolerance of 2% (before it fractures), whereas granulation tissue has a strain tolerance of 100%. Bony bridging between the distal and proximal callus can only occur when local strain (ie, deformation) is less than the forming woven bone can tolerate. Thus, hard callus will not bridge a fracture gap when the movement between the fracture ends is too great [22]. Nature deals with this problem by expanding the volume of soft callus. This results in a decrease in the local tissue strain to a level that allows bony bridging. This adaptive mechanism is not effective when the fracture gap has been considerably narrowed so that most of the interfragmentary movement occurs at the gap, producing a high-strain environment. Thus, overloading of the fracture with too much interfragmentary movement later in the healing process is not well tolerated [23].

At the cellular level, where the fundamental process of bone regeneration and tissue differentiation occurs, the situation is more complex. The biomechanical conditions, such as strain and fluid pressure, have an inhomogeneous distribution within the callus. The mechanoregulation of callus cells is a feedback loop in which the signals are created by the applied load and modulated by the callus tissue. Mechanical loading of the callus tissue produces local biophysical stimuli that are sensed by the cells. This may regulate cell phenotype, proliferation, apoptosis, and metabolic activities. With alteration of the extracellular matrix, and the associated changes in tissue properties, the biophysical stimuli caused by mechanical loading are modulated, producing different biophysical signals even with the same load. In normal fracture healing this feedback process reaches a steady state when the callus has ossified and the original cortex has regenerated. The biophysical signals themselves and the way they interact to produce the biological response are still being investigated. Several mechanoregulation algorithms have been postulated and have been shown to be consistent with some aspects of fracture healing, but they require...
further corroboration. Transduction of these stimuli into intracellular and extracellular messenger systems are being investigated; so both physical and molecular methods of treatment may be developed to treat delayed union and nonunion.

When fractures are splinted, movement of the fragments in relation to each other depends on the
- amount of external loading;
- stiffness of the splints;
- stiffness of the tissues bridging the fracture.

Multifragmentary fractures tolerate more motion between the two main fragments because the overall movement is shared by several fracture planes, which reduces the tissue strain or deformation at the fracture gap (Video 1.2-2). Today there is clinical experience and experimental proof that flexible fixation can stimulate callus formation, thereby accelerating fracture healing [20, 24]. This can be observed in diaphyseal fractures splinted by intramedullary nails, external fixators, or bridging plates.

- If the interfragmentary strain is excessive (instability), or the fracture gap is too wide, bony bridging by hard callus is not obtained in spite of good callus formation, and a hypertrophic nonunion develops (Tab 1.2-1) [25].

The capacity to stimulate callus formation seems to be limited and may be insufficient when large fracture gaps are to be bridged. In such cases dynamization (unlocking of the intramedullary nail or external fixator) may permit bony bridging by allowing the fracture gap to consolidate and increase its stiffness.

- Callus formation requires some mechanical stimulation and will not take place when the strain is too low. A low-strain environment will be produced if the fixation device is too stiff, or if the fracture gap is too wide [22]. Delayed healing and nonunion will result.

Again, dynamization may be the solution to the problem. If a patient is too immobile to load the operated leg, an externally applied load might be the way to stimulate callus formation [26].

4.4 Surgical fixation with absolute stability

If a fracture is bridged by a stiff splint, its mobility is reduced and little displacement occurs under functional load. Although stiffness of the implants contributes to reducing the mobility of the fracture, the only technique which will effectively abolish motion at the fracture site is interfragmentary compression.

Absolute stability abolishes deformation (strain) of repair tissue at the fracture site during physiological loading and results in direct bone healing. Reduction of strain to a level below the critical level will reduce stimulation of bone formation, causing the fracture to heal without visible callus.
In a low-strain environment bone heals directly by osteonal remodeling—the same homeostatic mechanism that exists for normal physiological bone turnover.

This process is also called primary bone healing. It is much slower than healing by callus formation and so the implant must not only provide and maintain absolute stability for a prolonged period of time, it must also be strong enough to resist fatigue failure during the prolonged healing period.

Direct bone healing is not the primary goal of this fracture fixation method but rather an unavoidable consequence of using a technique that obtains and maintains a perfect anatomical reduction. Anatomical reconstruction is the true goal of surgery in articular fractures and in some diaphyseal fractures such as the forearm.

Disturbance of bone biology or vascularity is far more serious than delayed union or nonunion resulting from a high-strain environment because the fixation is too flexible.

It takes much more experience and greater skill to treat a complication due to disturbed vitality than to fix a simple reactive (hypertrophic) nonunion, which just needs enhanced mechanical stability (chapter 5.2; 5.3).

4.4.1 Mechanics of techniques of absolute stability

Absolute stability is achieved by using a compressive preload and friction.

Compressive preload
Compression maintains close contact between two fragments, provided compression at the fracture site exceeds the traction forces acting at the fragment ends (Fig 1.2-8). Studies in sheep showed that compressive preload (static compression) does not produce pressure necrosis, neither in lag screws nor in plates compressing in an axial direction [27]. Even overloaded bone does not undergo pressure necrosis provided overall stability is maintained (Fig 1.2-8).

![Fig 1.2-8a-b](image-url) Stabilization by application of compression. The compressive preload prevents displacement of the fracture fragments and results in absolute stability as long as the compression produced is greater than any traction produced by function.
**Friction**
When fracture surfaces are pressed against each other, friction is produced. Friction counteracts shear forces that act tangentially, so sliding displacement is avoided (Fig 1.2-9). Shearing stems, in most cases, from torque applied to the limb, and this is more important than forces acting perpendicular to the long axis of the bone. The amount of resistance to shear displacement depends on the compression-induced friction and the geometry of the surfaces in contact (interdigitation). For smooth bone surfaces the normal forces produce somewhat less than 40% of friction. Rough surfaces allow a firm fixation and interdigitation of the fragments, which additionally counteracts displacement due to shear forces.

**4.4.2 Implants**

**Lag screws**
The lag screw is an implant which stabilizes a fracture by compression alone (chapter 3.2.1). The lag screw is applied to have purchase only in the remote cortex, and approximation between the thread and the head of the screw results in interfragmentary compression between the cortices. The fracture located between the far and near cortices is thereby compressed, and absolute stability is obtained by preload and friction.

In vivo experiments have shown that lag screws produce high loads of force (≥2,500 N) (Fig 1.2-10), and such forces are
maintained over a period which exceeds the time required for fracture healing. Compression produced by a lag screw acts optimally from within the fracture, in contrast to compression produced by plates (chapter 3.2.2).

There are two disadvantages of compression fixation by lag screws alone. Lag screws provide high compression force, but the lever arm of such compression is, in most instances, too small to resist functional loading. This applies to both bending and shearing because the area of compression is small when viewed from the center of the screw. Thus, in diaphyseal fractures, lag screws must always be combined with a plate that protects them from these forces (= protection plate, previously called neutralization plate). The other disadvantage of lag screw fixation is its lack of tolerance to single overload. When a screw thread strips, it loses its compressive action and is unable to recover its function. This is a contrast to plate fixation where loss of function of a single screw may be compensated by the rest of the fixation.

- Lag and plate screws must not be tightened to a level where they start to give way. With this mode of application, the bone threads are partially damaged and/or the screws are plastically deformed and may fail.

The more the screw is tightened, the greater the risk that it will fail. Either the bone thread strips or the metal breaks with complete loss of function. It is especially important to consider this when titanium screws are used, as titanium provides little prewarning to the surgeon who may apply too much torque. Titanium screws are only slightly weaker than steel screws (chapter 1.3), but their ductility (plastic deformation before rupture) is low.

**Plates**

A fracture fixed with one or more lag screws results in fixation without motion (absolute stability), but in general such fixation tolerates only minimal loading. A splint bridging the fracture site can reduce the load placed on the screws. Therefore, lag screws are usually combined with plates acting as splints to protect the screw by reducing shear or bending forces. The term protection plate (earlier called neutralization plate) refers to a plate functioning in this way.

A plate can be used to function in five different ways (chapter 3.2.2):
- protection;
- compression;
- tension band;
- bridging;
- buttress.

A plate may be applied to one side of a fracture and then tensioned (by using eccentric placement of screws in the plate or by using the articulated compression device) to compress the bone (and fracture) along its long axis. This is only effective in simple transverse or short oblique fractures. However, when a straight plate is applied to a straight bone, this will produce
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Compression underneath the plate with slight distraction (tension) of the opposite cortex (Fig 1.2-11). This is not a stable situation. Overbending of the plate, so there is a small gap between the plate and the bone at the level of the fracture, will achieve compression of both the near and far cortex and produce absolute stability (Fig 1.2-12). A plate may be placed on the tension side of the bone to act as a tension band. When the bone is loaded, the plate converts tension into compression at the far cortex and produces absolute stability. This principle is discussed in detail in chapter 3.2.3.

A buttress plate is used in the metaphyseal areas. A buttress is a construction that resists axial load by applying force at 90° to the axis of potential deformity. Under such conditions, the plate initially carries full functional load. It can be used to provide absolute stability and is often combined with lag screws.

A bridging plate is used in multifragmentary fractures. It is used to fix only the two main fragments and restore length, alignment, and rotation. There is minimal disturbance of the

Fig 1.2-11  Compression with a straight plate. This photoelastic picture shows that by applying tension to the plate, compression of the plated bone segment can be produced. Thus, compression acts within the bone along its long axis. Such compression is effective only in transverse fractures. With a straight plate, there is only compression in the near cortex, underneath the plate.

Fig 1.2-12  Compression with a prebent plate. Symmetrical compression may be achieved by prebending the plate. The slightly curved plate is applied to the bone surface with the middle part elevated. When the screws are tightened, the far cortex opposite to the plate is compressed as well.
1.2 Biology and biomechanics in bone healing

fracture site and no fixation of further fragments. This technique always provides relative stability with healing by callus formation. A comprehensive description of the function and application of plates is given in chapter 3.3.2.

The locking compression plate (LCP) can be used to function in the five different modes described above. Thus, the LCP can be used to provide absolute or relative stability. It resembles a LC-DCP but has combination holes. The smooth part of the dynamic compression unit allows insertion of conventional screws so the plate can be used in the same way as a DCP or LC-DCP. The threaded part of the combination hole allows locking head screws to be inserted to produce a mechanical coupling between the plate and the screw. For multifragmentary fractures, the LCP can be used as a standard bridging plate. However, if locking head screws are used for the entire fixation, the plate is not compressed against the cortex and acts like an external fixator. This is the internal fixator principle. It provides relative stability with minimal interference with the blood supply to the fracture.

- When using the LCP, it is essential that the surgeon understands the different functions of the plate and knows how to use this device to achieve the goals of surgery. Careful preoperative planning is essential and must include the order of screw insertion, which can fundamentally alter the biomechanical function of this device.

The use of the LCP is explained in detail in chapter 3.3.4.

External fixators
Circular external fixators, as developed by Ilizarov, allow complete control of length, alignment, and rotation of a fracture. These devices can be used to provide absolute stability. The same principle applies when circular frames are used to treat hypertrophic nonunions, where the provision of absolute stability will allow rapid fracture union. Circular frames can also be used to apply compression across oblique fractures, but this requires careful planning and a more complex frame design. The frame adjustments that allow compression in different planes are difficult to calculate but computer programs are now available to aid the surgeon in achieving this goal.

4.4.3 Mechanobiology of direct or primary fracture healing
Bone healing is different in cortical and cancellous bone. The basic elements correspond qualitatively, but as the vascularity and the volume to surface ratio are very different, the speed and reliability of healing is generally better in cancellous bone.

Diaphyseal fractures
In the diaphysis, absolute stability is achieved by means of interfragmentary compression to maintain the fracture fragments in permanent apposition (chapter 3.2.2). Pain will subside and allow for early functional treatment within a few days of surgery.

Radiologically, only minor changes can be observed: Under absolutely stable fixation, there is minimal visible callus formation or none at all [28]. The fact that the fragment ends are closely approximated means that only a fine line can be seen on x-rays. This renders the judgment of fracture healing difficult. A gradual disappearance of the fracture line with trabeculae growing across this line is a good sign, while a widening of the gap is a sign of instability. The surgeon judges the progress of healing by the absence of radiological signs of irritation, such as bone resorption or the formation of a cloudy “irritation” callus, as well as by clinical symptoms, such as the presence or absence of pain and swelling.
The histological sequence of healing under conditions of absolute stability:

- In the first few days after surgery there is minimal activity within bone near the fracture site. The hematoma is resorbed and/or transformed into repair tissue. The swelling subsides while the surgical wound heals.
- After a few weeks, the Haversian system starts to remodel the bone internally as visualized by Schenk and Willenegger (Fig 1.2-13; 1.2-14) [29]. At the same time, gaps between imperfectly fitting fragment surfaces—if stable—will start to fill with lamellar bone, the orientation of which is transverse to the long axis of the bone.
- In subsequent weeks, the cutter heads of the osteons reach the fracture and cross it wherever there is contact or only a minute gap [30]. The newly formed osteons crossing the gap provide a kind of microbridging or interdigitation.

Fractures in cancellous bone

Fractures around the metaphysis have a comparatively large fracture surface with good vascularity. This offers the opportunity of good fixation in terms of bending and torque, and thus these fractures tend to be more stable, and healing occurs more rapidly. Radiological evaluation is somewhat impeded by the complex 3-D structure of trabecular cancellous bone. The main histological activity seen in fracture healing of cancellous bone occurs at the level of the trabeculae. Healing—due to the larger surface per volume—is likely to occur faster than in cortical bone. Because vascularization of cancellous bone is better than in cortical bone, necrosis is less likely to occur.

The advantage of absolute stability is that it maintains perfect reduction of the articular surface and allows early functional rehabilitation. The disadvantages are that internal Haversian...
remodeling starts late and takes a long time and that the absence of any movement at the fracture gap does not stimulate callus formation. Therefore, the implant alone must provide stable fixation initially and for a longer period than fractures treated with relative stability.

**Recovery of blood supply**

Absolute stability also has positive effects on the blood supply. Under stable conditions, blood vessels may cross a fracture site more easily. Despite the deleterious effects of surgical procedures used to achieve absolute stability, once obtained, it supports the repair of blood vessels (Fig 1.2-15).

In plate fixation, the comparably large contact area (footprint) of conventional plates is considered a disadvantage. Bone tolerates mechanical loading quite well and protects its inner blood vessels from being affected by it. The blood vessels entering bone from the periosteal and endosteal sides are, however, very sensitive to any external contact. When plates are placed onto the bone surface, they are likely to disturb the periosteal blood supply. In conventional plating, part of the stability is obtained by friction between the plate and bone, which requires a minimum area of contact. Extensive and continuous contact between any implant and bone results in circumscribed areas of bone necrosis in the cortex directly underneath the plate. This may lead to temporary porosis of the bone and, exceptionally, to sequestration. Recent studies have shown that reduction of the implant-bone interface may improve resistance to local infection and enhance fracture healing (Fig 1.2-16).

**Fig 1.2-15** The effect of stability on revascularization. The osteotomy of a rabbit tibia has been reduced and stably fixed. As early as 2 weeks after complete transection of the bone and medullary cavity the blood vessels have reconstituted and are functioning, as this angiography at 14 days shows.

**Fig 1.2-16** Bridging plate. The plate spans a critical fracture area and is fixed only near its two ends. Thus, periosteal contact at the fracture site that could impede circulation is avoided and there is the possibility of placing a bone graft under the bridge.
Today’s state-of-the-art technology of surgical fracture treatment offers interesting possibilities, but it is wide open to improvements in terms of surgical technique and instruments/implants. The goal is a simple and cost-effective technology, which allows reliable healing and early return to full function of the limb and patient. The technology must be of appropriate quality and its application must be safe and easy for surgeons of all levels of skills to learn and comprehend. However, any advances will be based upon the building blocks of basic science and the principles described in this book. It is essential that the practicing surgeon has a clear understanding of both.

**Bibliography**


