1 Principles of Internal Fixation

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1.1 Introduction

1.1.1 Mechanical Properties of Bone

The principal mechanical function of bone is to act as a supporting structure and transmit load. The loads which bone has to withstand are those of pure compression, those of bending, which result in one cortex being loaded in tension and the other in compression, and those of torque, or twisting. Bone is strongest in compression and weakest in tension. Fractures as a result of pure compression are therefore rare and occur only in areas of cancellous bone with a thin cortical shell. Thus, we find pure compression fractures in such areas as the metaphyses, vertebral bodies, and the calcaneus. Transverse, oblique, and spiral are the fracture patterns commonly seen in tubular bone.

Transverse fractures are the result of a bending force (Fig. 1.1). They are associated with a small extrusion wedge that is always found on the compression side of the bone. If this extrusion wedge comprises less than 10% of the circumference, the fracture is considered a simple transverse fracture. If the extruded fragment is larger, the fracture is considered a wedge fracture, and the fragment a bending or extrusion wedge. Because it is extruded from bone under load, it retains little of its soft tissue attachment and has therefore, at best, a precarious blood supply. This must be kept in mind when planning an internal fixation. Attempts to secure fixation with lag screws of such extruded fragments may result in their being rendered totally avascular. If the extruded wedge is very small, as in fractures of the radius and ulna, they may be ignored. If larger, as in fractures of larger tubular bones, it is best to leave them alone and use indirect reduction techniques to preserve whatever blood supply remains, and either use a locked intramedullary nail for fixation, or if this is not possible, a bridge plate.

Oblique fractures are also the result of a bending force. The extrusion wedge remains attached to one of the main fragments. The fissure between it and the main fragment is not visible on X-ray. If looked for at the time of an open reduction, it can often be found. During closed intramedullary nailing this undisplaced extrusion wedge is often dislodged and becomes apparent on X-ray.

Spiral fractures are the result of an indirect twisting force (Fig. 1.1). They often occur in combination with spiral wedge fragments of corresponding configuration. These fragments are larger and retain their soft tissue attachment. It is frequently possible to secure them with lag screws without disrupting their blood

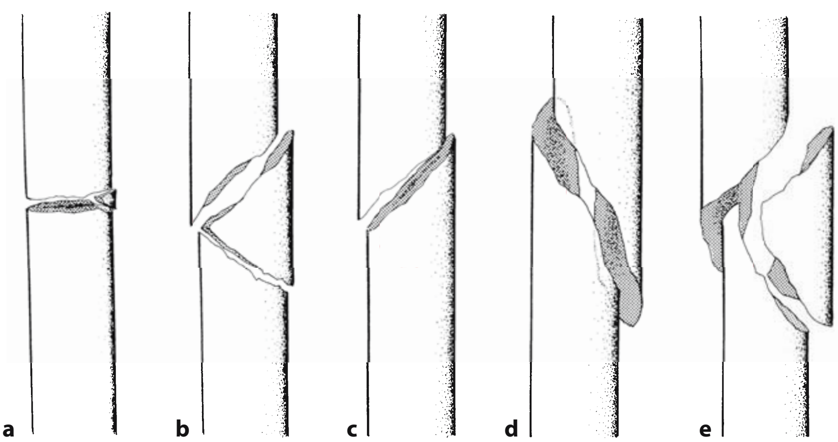


Fig. 1.1a–e. Types of fracture patterns. A lateral bending force can result in transverse fracture (**a**), extrusion or bending wedge fractures (**b**), or oblique fractures (**c**) in which the extrusion wedge remains attached to one of the main fragments. A twisting or torsional force may result in a spiral fracture (**d**) or one with a single or multiple spiral wedge fragments (**e**)

supply. These differences in the degree of soft tissue attachment and preserved blood supply are important to consider in the choice of internal fixation. If one is dealing with a spiral wedge or a very large extrusion wedge, then their soft tissue attachment and blood supply will likely be preserved, and an attempt at absolutely stable fixation with lag screws would not render them avascular. If on the other hand the extrusion wedge is small of if the wedge is fragmented or if one is dealing with a complex fracture, it is best not to attempt absolutely stable fixation but resort to splinting and secure the fracture with a bridge plate. These remarks apply, of course, to fractures in metaphyseal areas. Diaphyseal fractures are nailed by preference except in the forearm and humerus.

1.1.2 Types of Load and Fracture Patterns

Bone is a viscoelastic material. Fractures are therefore related not only to the force but also to the rate of force application. Much less force is required to break the bone if the force is applied slowly and over a long period of time than if it is applied rapidly: bone is better able to withstand the rapid application of a much greater force. This force is stored, however, and when the bone can no longer withstand it and finally breaks, it is dissipated in an explosive and implosive fashion, causing considerable damage to the soft tissue envelope. A good example of this is the skier who walks away from a spectacular tumble, only to break his leg in a slow, twisting fall. The amount of energy and the rate of force application are important factors since they determine the degree of associated damage to the soft tissue envelope. We therefore distinguish between low- and high-velocity injuries.

Low-velocity injuries have a better prognosis. They are more commonly the result of an indirect force application such as a twist, and the associated fractures are spiral and the comminution is rarely excessive. In high-velocity injuries the fractures are not only more fragmented but also associated with a much greater damage to the enveloping soft tissues, because of the higher energy dissipation and because of the direct application of force.

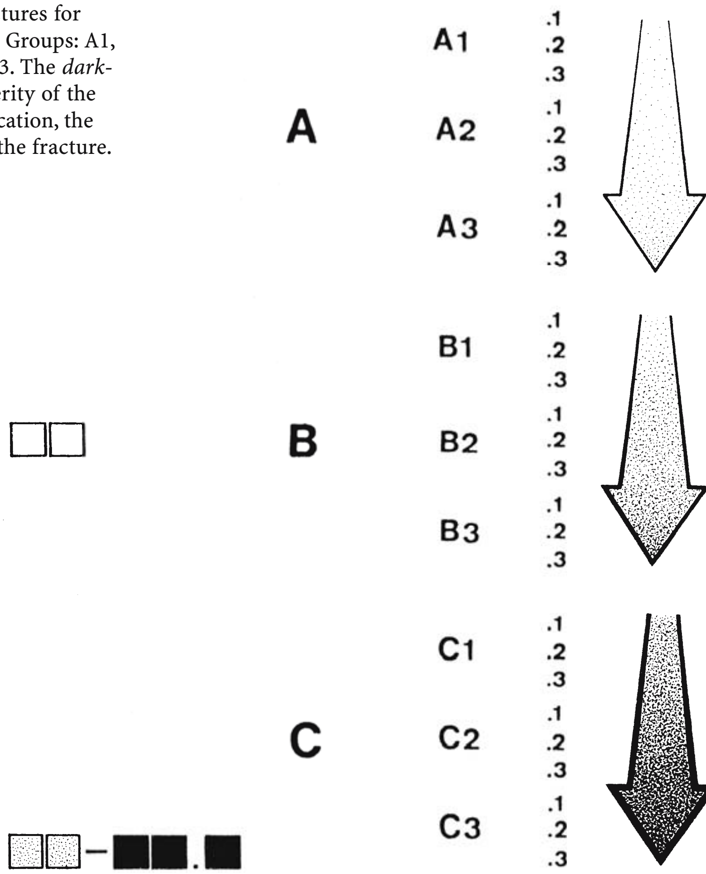
1.1.3 Classification of Fractures

The classification of fractures followed in this book is based on the *Comprehensive Classification of Fractures of Long Bones* (Müller et al. 1990). The unique feature of this system of classification is that the principles of the classification and the classification itself are not based on the regional features of a bone and its fracture patterns nor are they bound by convention of usage or the popularity of an eponym. They are generic and apply to the whole skeleton. The philosophy guiding the classification is that a classification is worthwhile only if it helps in evolving the rationale of treatment and if it helps in the evaluation of the outcome of the treatment (Müller et al. 1990). Therefore the classification must indicate the severity of the fracture, which in this classification indicates the morphological complexity of the fracture, the difficulties to be anticipated in treatment, and its prognosis. This has been accomplished by formulating the classification on the basis of repeating triads of fracture types, their groups and subgroups, and by arranging the triads and the fractures in each triad in an ascending order of severity. Thus there are three fracture types A, B, and C in ascending order of severity. Each fracture type has three groups, A1, A2, and A3, B1, B2, and B3, and C1, C2, and C3, and each group three subgroups, A1.1, A1.2, etc. The groups and the subgroups are also organized in an ascending order of severity (please see Fig. 1.2). This organization of fractures in the classification in an ascending order of severity has introduced great clinical significance to the recognition of a fracture type. The identification of the Type indicates immediately the severity.

The classification considers a long bone to have a diaphyseal segment and two end segments (Figs. 1.3, 1.4). Because the distinction between the diaphysis and the metaphysis is rarely well defined anatomically, the classification makes use of the rule of squares to define the end segments with great precision (Fig. 1.4). The location of the fracture has also been simplified by noting the relationship that the center of the fracture bears to the segment.

The authors of the *Comprehensive Classification of Fractures of Long Bones* have also developed a new terminology that is so precise that it is now possible to describe a fracture verbally with such accuracy that its pictorial representation is superfluous. The new precise terminology divides fractures into simple and multifragmentary (Fig. 1.5). The multifragmentary fractures are further subdivided into wedge and complex fractures, not on the basis of the number of fragments, but rather on the key issue of whether after reduction the main fragments have retained contact or not. In treatment this is, indeed, the essence of severity. Thus, a multifragmentary fracture with some contact between the main frag-

Fig. 1.2. The scheme of the classification of fractures for each bone segment or each bone. Types: A, B, C; Groups: A1, A2, A3, B1, B2, B3, C1, C2, C3; Subgroups: .1, .2, .3. The *darkening of the arrows* indicates the increasing severity of the fracture. *Small squares:* The first two give the location, the next three the morphological characteristics of the fracture. (From Müller et al. 1990)



ments is considered a wedge fracture. It has a recognizable length and rotational alignment. This is lost in a complex fracture where contact between the main fragments cannot be established after reduction (Fig. 1.6). Articular fractures are defined as those that involve the articular surface regardless of whether the fracture is intracapsular or not. A further distinction exists between partial and complete articular fractures (Fig. 1.7).

The diagnosis of a fracture is given by coupling the location of the fracture with its morphologic complexity. To facilitate computer entry and retrieval of the cases, an alphanumeric code has been created. Computers deal with numbers and letters better than with words. The bones of the skeleton have been assigned numbers (Fig. 1.8). The segments are numbered from one to three proceeding from proximal to distal. Thus it is possible to express the location of a fracture by combining the number of the bone with the number expressing the involved segment: for instance, a fracture of the proximal segment of the humerus would be 11- and a fracture of the distal femur would be 33-. The morphological nature of the fracture is expressed by the combination of the letters

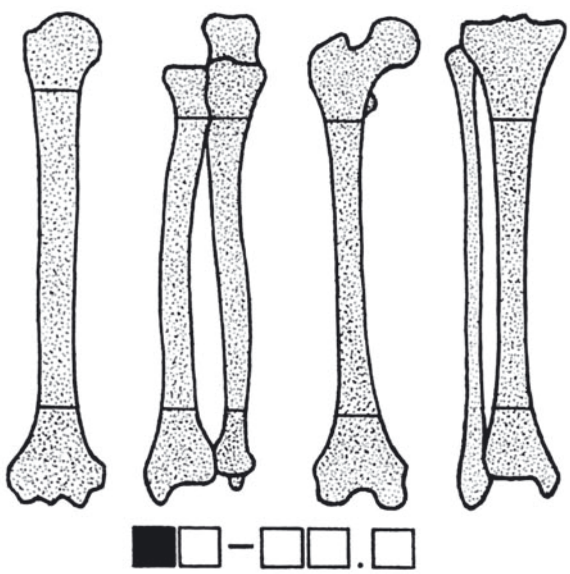


Fig. 1.3. The long bone. *1*, Humerus; 2, radius/ulna; *3*, femur; *4*, tibia/fibula. The *blackened square* indicates the portion of the alphanumeric code being illustrated. (From Müller et al. 1990)

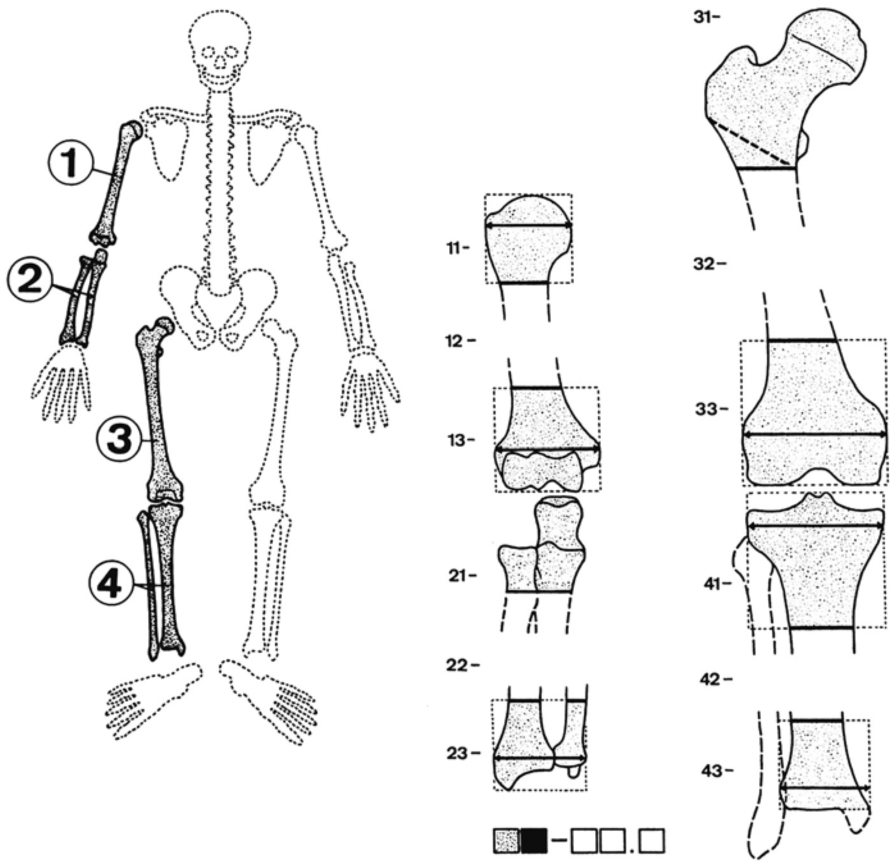


Fig. 1.4. The determination of the segments of long bones. The different squares are parallel to the long axis of the body and correspond to the end segments. The malleolar segment (44–) is not represented here as it cannot be compared with the other end segments: 11–, 12–, 13–, 21–, 22–, 23–, 31–, 32–, 33–, 41–, 42–, 43–. (From Müller et al. 1990)

A, B, and C, which denote the Type; with the numbers 1, 2, and 3, such as A1, A2, A3, B1, B2, etc., to denote the Groups, and A1.1, A1.2, A1.3, B1.1, B1.2, etc., to denote the Subgroups. The diagnosis can be coded using an alphanumeric code (Fig. 1.9). As stated, this alphanumeric code is intended strictly for computer entry and retrieval and not for use in verbal communication. In verbal communication the clinician should use the terminology which is so precise that it describes the full essence of the fracture, making a pictorial representation of the fracture no longer necessary.

We have validated this fracture classification in two separate clinical studies (J. J. Schatzker and P. Lichtenhahn, unpublished data; J. Schatzker and H. Tornkvist, unpublished data). The inter- and intraobserver concordance has been evaluated for fracture types, groups, and subgroups. Concordance for fracture types was close to 100%, for fracture groups between 80% and 85%, but for fracture subgroups only between 50% and 60%. We feel, therefore, that the clinician should rely principally on the recognition of the fracture types and groups. Classification into fracture subgroups should be reserved only for research studies.

The issue of intra- and interpersonal reliability of classification systems has received a great deal of attention in the recent literature. The authors of these articles fail to discern the essence of the cause of the high discordance. The discordance is either the result of the classifier not knowing the classification system or because the classifier lacked essential data, or relied on pictorial representation of the different fractures, and had no method available to check whether all the essential information was available at the time the fracture was being classified. In order to provide the classifier with a check list of essential data which must be available before a fracture can be classified, the authors of the Comprehensive Classification System have developed a system of binary questions which allow the classifier to determine with precision whether all the essential data necessary to classify a fracture are available. If not, further imaging may be necessary before the classification can be attempted. At times essential information, for instance the damage to the articular cartilage of the femoral head in an acetabular fracture, may not be available until the surgery has been completed.

The Comprehensive Classification System has been adopted by both the Arbeitsgemeinschaft für Osteo-

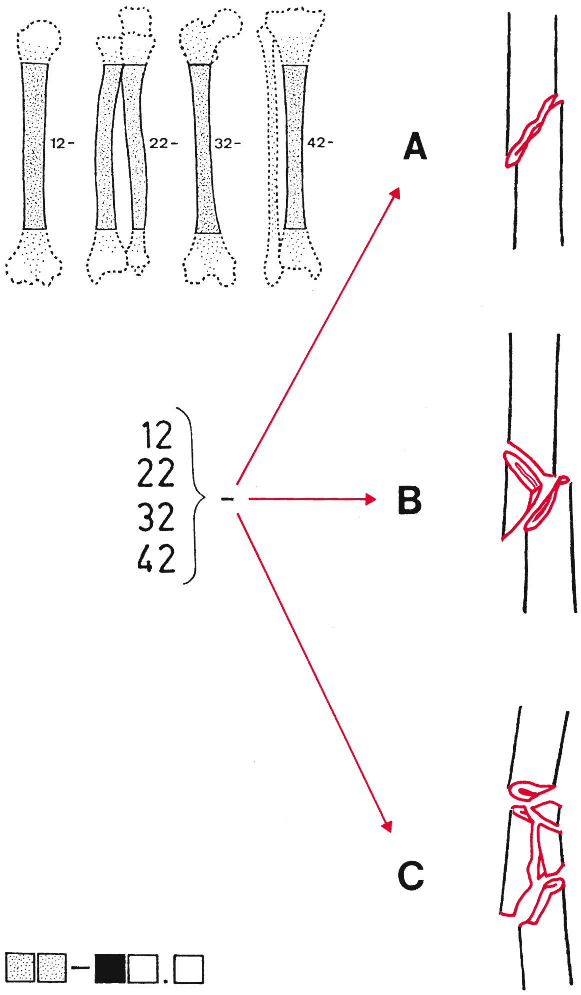


Fig. 1.5. The diaphyseal fracture types. *A*, simple fracture; *B*, wedge fracture; *C*, complex fracture. (From Müller et al. 1990)

synthesefragen/Association for the Study of Internal Fixation (AO/ASIF) and Orthopaedic Trauma Association (OTA) as their classification systems. Currently these groups are attempting to complete the classification of fractures and dislocations not included in the published version of the Comprehensive Classification System and to subject their efforts to clinical validation.

The classification of the soft tissue injury associated with open fractures continues to be a problem requiring further elaboration. Many observers have attempted to grade open fractures (Allgöwer 1971; Gustilo and Andersson 1976; Tscherne and Gotzen 1984; Lange et al. 1985). A further classification of the soft tissue component of an injury was presented in the third edition of the Manual of Internal Fixation (Müller et al. 1991). In this most recent attempt a code for the injury is assigned to each of the elements of the soft tissue envelope rather than using an existing classification system. A new classification scheme which would characterize the morphological components of the soft tissue injury, identify its severity, and indicate the potential functional loss in a simple and comprehensive manner, and which could be expressed in a simple code, would be of great value clinically and in research.

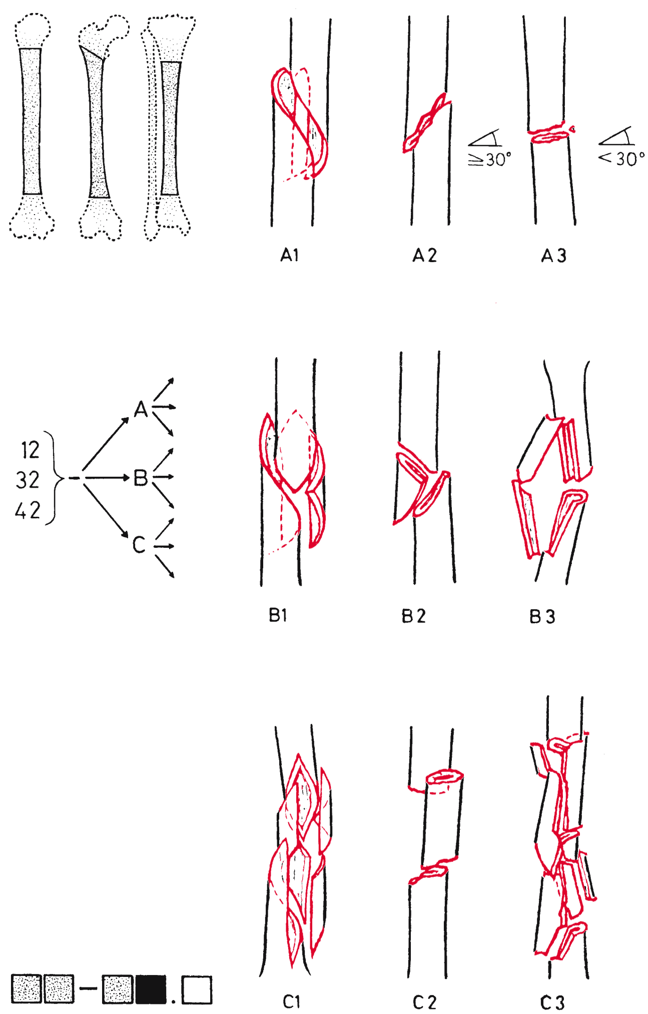


Fig. 1.6. The groups of the diaphyseal fractures of the numberus, femur, and tibia/fibula. *A1*, simple fracture, spiral; *A2*, simple fracture, oblique (L30°); *A3*, simple fracture, transverse (<30°); *B1*, wedge fracture, spiral wedge; *B2*, wedge fracture, bending wedge; *B3*, wedge fracture, fragmented wedge; *C1*, complex fracture, spiral; *C2*, complex fracture, segmental; *C3*, complex fracture, irregular. (From Müller et al. 1990)

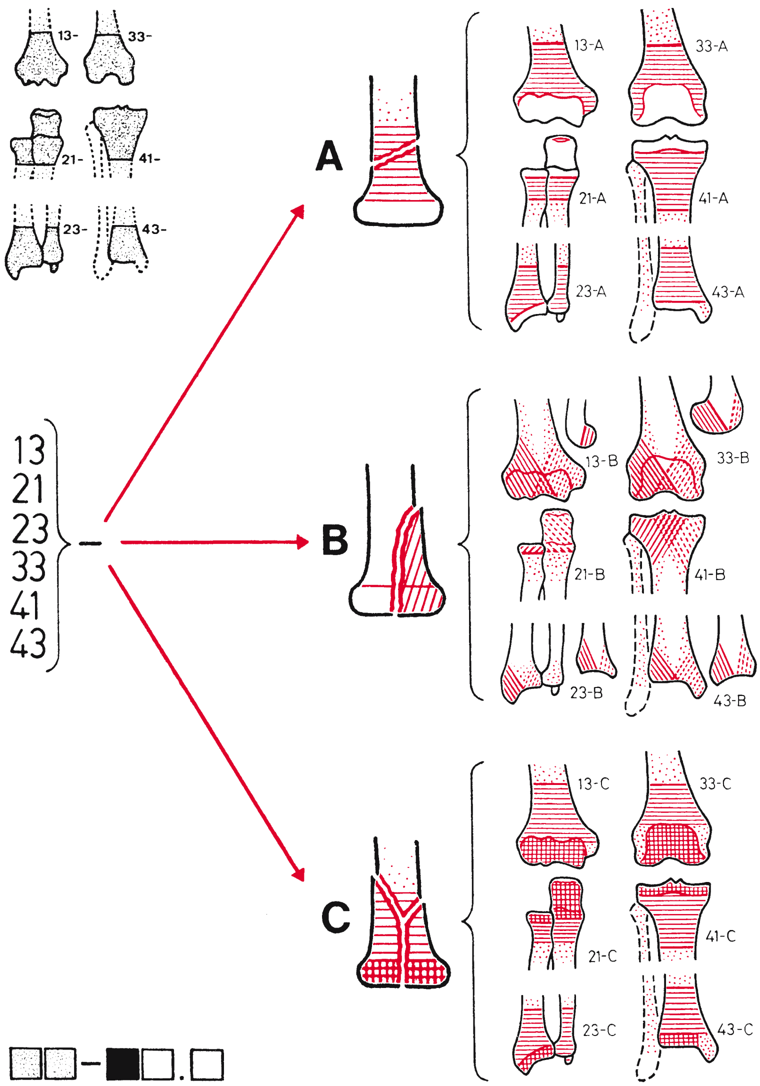


Fig. 1.7. The fracture types of the segments *13-* and *33-*, *21-* and *41-*, *23-* and *43-*. *A*, extra-articular fractures; *B*, partial articular fracture; *C*, complete articular fracture. (From Müller et al. 1990)

1.1.4 Effects of Fracture

When a bone is fractured, it loses its structural continuity. The loss of the structural continuity renders it mechanically useless because it is unable to bear any load.

1.1.5 Soft Tissue Component and Classification of Soft Tissue Injuries

We have alluded to the poorer prognosis of high-velocity injuries because of the greater damage to the soft tissue envelope and to the greater devitalization of the involved bone. Long-term disability following a fracture is almost never the result of damage to the bone itself; it is the result of damage to the soft tissues and of stiffness of neighboring joints.

In a closed fracture the injury to the surrounding tissue evokes an acute inflammatory response, which is associated with an outpouring of fibrinous and proteinaceous fluid. If, after the injury, the tendons and muscles are not encouraged to glide upon one another, inflammation may develop and lead to the obliteration of tissue planes and to the matting of the soft tissue envelope into a functionless mass.

In an open fracture, in addition to the possible scarring from immobilization, there is direct injury to the muscles and tendons and in such cases the effects of infection must be reckoned with. Indeed, infection is the most serious complication of trauma because, in addition to the scarring related to the

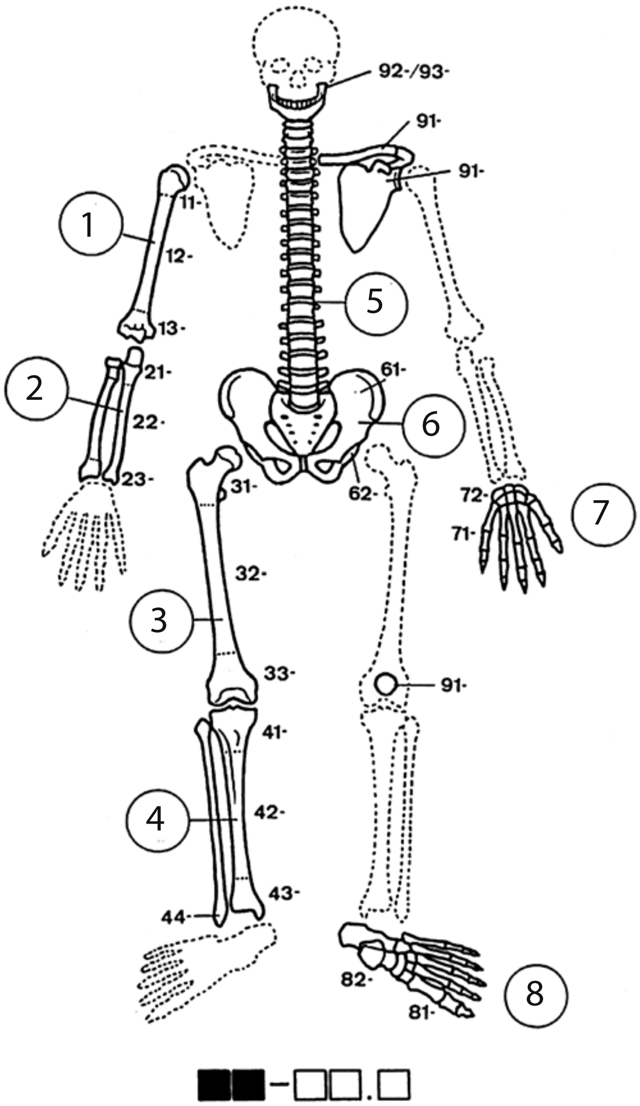


Fig. 1.8. The bones and their segments. An overview of the whole skeleton. *1,* Humerus and its three segments: proximal, diaphyseal, and distal; *2,* radius/ulna and its three segments: proximal, diaphyseal, and distal; *3,* femur and its three segments: proximal, diaphyseal, and distal; *4,* tibia/fibula and its four segments: proximal, diaphyseal, distal, and malleolar; *5,* spine and its three segments: cervical, thoracic, and lumbar; *6,* pelvis and its two segments: extra-articular and the acetabulum; *7,* hand; *8,* foot; *9,* other bones: *91.1,* patella; *91.2,* clavicle; *91.3,* scapula; *92,* mandible; *93,* facial bones and skull. (From Müller et al. 1990)

initial trauma, infection compounds the fibrosis as a result of the associated tissue damage and because of the prolonged immobilization that is frequently necessary until the infection is cured.

Stiffness in adjacent joints in nonarticular fractures is also the result of immobilization. Prolonged immobilization leads to atrophy of the articular cartilage, to capsular and ligamentous contractures, and to intra-articular adhesions. The joint space normally filled with synovial fluid becomes filled with adhesions that bind the articular surfaces together. Added to the local effects is, of course, the tethering effect of the scarred soft tissues.

Although the significance of the soft tissue component of open fracture injuries has been recognized for a long time, the soft tissue component of closed injuries has only recently been classified (Tscherne and Brüggemann 1976; Tscherne and Östern 1982; Tscherne and Gotzen 1984; Müller et al. 1991).

1.2 Aims of Treatment

The loss of function of the soft tissue envelope due to scarring and secondary joint stiffness can only be prevented by early mobilization. Thus, modern fracture treatment does not focus on bone union at the expense of function but addresses itself principally to the restoration of function of the soft tissues and adjacent joints. A deformity or a pseudarthrosis is relatively easy to correct in the presence of good soft tissue function, while scarring, obliteration of the soft tissue gliding planes, and joint stiffness are often permanent. The modern fracture surgeon will therefore direct treatment to the early return of function and motion, with bone union being considered of secondary importance.

Modern functional fracture treatment does not denote only operative fracture care. It makes use of specialized splinting of the bone in special braces that allow an early return of function and motion. There are, however, limitations to the nonoperative system, which we will address as we discuss the different frac-

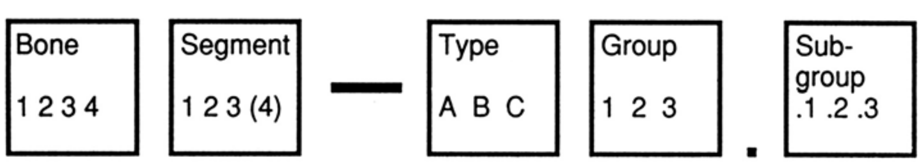


Fig. 1.9. The coding of the diagnosis

tures. It can be applied to fractures where angulation, rotation, and shortening can be controlled. Thus, it is limited only to certain long bone fractures. Its application to intra-articular and periarticular fractures is very limited.

Early return of full function following fracture can be achieved only by sufficiently stable internal fixation which will abolish fracture pain and which will allow early resumption of motion with partial loading without the risk of failure of the fixation and resultant malunion or nonunion. With nonfunctional methods full return of function is rarely achieved, and then only after a prolonged rehabilitation period.

1.3 Previous Experience with Internal Fixation

Internal fixation is not a new science. The first half of the twentieth century has provided us with ample documentation of the results of unstable internal fixation. Surgery has frequently proved to be the worst form of treatment. It destroyed the soft tissue hinges, interfered with biological factors such as the blood supply and the periosteum, and was never sufficiently strong or stable to permit active mobilization of the limbs with partial loading. Supplemental external plaster fixation was often necessary. The emphasis was on bone healing and not on soft tissue rehabilitation. Healing became evident when callus appeared. Unfortunately, unstable internal fixation was unpredictable and uncertain, and it frequently resulted in delayed union, nonunion, or deformity. When union did occur, instead of signifying the end of treatment it merely signaled the beginning of a prolonged phase of rehabilitation designed to regain motion in the soft tissue envelope and in the stiff joints. The ravages of this prolonged nonfunctional form of treatment were such that open reduction and internal fixation were looked upon as the last resort in the treatment of a fracture.

1.4 Rigidity and Stability

It is important to distinguish between rigidity and stability. Rigidity is the physical property of an implant. It refers to its ability to withstand deformation. Thus, in an internal fixation the fixation devices employed may be rigid but the fixation of the fragments may be unstable.

The introduction of compression introduced stability. Stability was achieved not by rigidity of the implant, but rather by impaction of the fragments. The intimate contact of the fragments brought about by compression restored structural continuity and stability and permitted the direct transfer of forces from fragment to fragment rather than via the implant. Stable fixation restores load-bearing capacity to bone. This greatly diminishes the stresses borne by the implant and protects the implant from mechanical overload or fatigue failure.

Key (1932) and Charnley (1953) were the first to make use of compression in order to achieve stable fixation. Both applied it to broad cancellous surfaces by means of an external compression clamp. Similar attempts to achieve union of the cortex failed. The resorption around the pins of the external fixator employed to stabilize the cortical fragments was thought to be due to pressure necrosis of the cortex. Cancellous surfaces under compression united rapidly, and it was thought initially that compression provided an osteogenic stimulus to bone. The failure of the cortex to unite led to general acceptance of the thesis that cancellous and cortical bone behaved differently and that they probably united by different mechanisms.

Since then it has been demonstrated that, under conditions of absolute stability, both cancellous and cortical fragments heal by what has been referred to as primary direct or vascular bone union (primary bone healing). The simple external fixator of Charnley, applied closely to broad, flat cancellous surfaces of an arthrodesis, was able to achieve absolute stability. The same system applied to diaphyseal bone, where tubular fragments rather than broad, flat surfaces were in contact, resulted in a system of relative instability with micromotion between the fragments. The resorption around the pins and at the fracture was due to motion and not due to pressure necrosis.

Danis in 1949 (Müller et al. 1970) was the first to demonstrate that cortical fragments stabilized by a special plate, which was able to exert axial compression and bring about absolute stability at the fracture, united without any radiologically visible callus. Danis referred to this type of union as "primary bone healing." Studies on experimental models of healing under conditions of absolute stability by Schenk and Willenegger (1963) revealed a different type of union than that commonly associated with the healing of fractures. Union seemed to occur by direct formation of bone rather than by callus and endochondral ossification. Different events were seen where bone was in contact and where gaps were present.

In areas of contact the healing was seen to be the result of proliferation of new osteons which arose from remaining open Haversian systems. The osteons, the so-called cutting cones, grew parallel to the long axis of the bone, through the necrotic bone ends, and then across the fracture. These osteons can be viewed as a myriad of tiny bone dowels that reestablish the continuity of bone. The capillary buds that sprang from the capillaries became cutting cones. These consisted of osteoclasts, followed by the capillary bud, surrounded by a cuff of osteoblasts that were laying down bone. In this way, there was simultaneous bone resorption and deposition. This bridging of a fracture by osteons, which gives rise to an osteonal union, can occur only where bone is in direct contact and where there is absolute stability of the fragments without any movement at the interface. In this type of union there is no net resorption at the fracture interface. For every bit of bone removed, new bone is laid down. Under these circumstances, internal fixation does not lead to a relative distraction of the fragments, because no absolute resorption occurs.

Areas of bone separated by gaps demonstrated first of all an invasion of the gaps by blood vessels with surrounding osteoblasts. The osteoblasts laid down osteoid that served to bridge the gaps and to permit stage two to begin. Stage two is identical to contact healing, described above. Examination of human material (R. Schenk, personal communication) from autopsies of patients who had had fractures operated upon revealed that the experimentally noted phenomena of contact and gap healing also occurred clinically. The study of material from patients whose fractures had zones of comminution and which were fixed with lag screws and plates to secure absolutely stable fixation revealed that, although healing seemed undisturbed, free fragments, whose blood supply had been interfered with, lagged very much behind in the degree of revascularization and remodeling. Thus, the rate of revascularization and union was seen to be influenced by the severity of comminution, the degree of initial displacement – for this has a bearing on the severity of devitalization of the fragments, by direct reduction and by the methods of fixation as well as by the presence and degree of severity of the soft tissue lesion. These observations of interference with blood supply and delayed revascularization are of particular importance with regard to implant removal, for not every fracture, nor all areas of the same fracture, will have advanced to the same degree of remodeling at a given time from injury. With primary bone healing we see a biological phenomenon which is different from healing under conditions of relative stability which is associated with the formation of callus. The so-called primary bone healing is in the early stages of healing weaker than bone bridged by a peripheral concentric callus.

1.5 Methods of Absolutely Stable Fixation

1.5.1 Lag Screw

Compression exerts its beneficial effect on bone union by creating an environment of absolute stability where no relative micromotion exists between the bone fragments. Healing is by primary union. Therefore, viability of the bone fragments is not a prerequisite to union. As long as absolute stability is maintained, the fragments will be revascularized and remodeled and primary bone union will occur. Articular cartilage also benefits from compression because absolute stability is necessary for articular cartilage regeneration and healing (Mitchell and Shepherd 1980). Interfragmental compression results in impaction of the fragments and in a marked increase in frictional resistance to motion. It is therefore the most important and efficient method of restoring functional and structural continuity to bone. It also greatly diminishes the forces borne by an internal fixation because the load transfer occurs directly from fragment to fragment. Stability is thus achieved, not by rigidity of the implant, but rather by compression and bone contact.

The simplest way of compressing two fragments of bone together is to lag them together with a *lag screw*. The lag screw is the simplest and most efficient implant in use for securing interfragmental compression (Fig. 1.10).

The insertion of a screw into bone results in local damage that triggers the mechanisms for immediate repair. This is seen histologically as the formation of new bone that closely follows the profile of the screw threads. Thus, after the insertion of a screw, as healing occurs, the holding power of the screw increases, reaching its peak between the sixth and eighth weeks. The holding power then gradually declines to a level well above what it was at the time of insertion (Schatzker et al. 1975b). This occurs because, as the bone

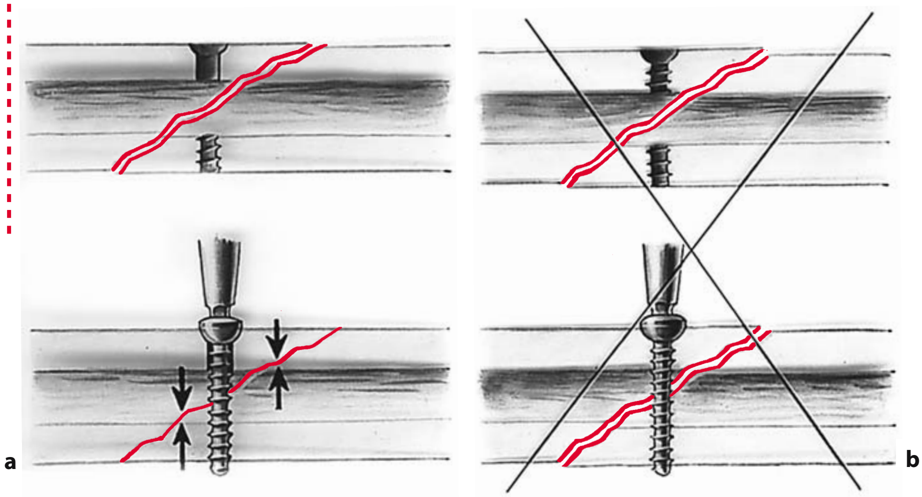


Fig. 1.10a, b. The lag screw. **a** The hole next to the screw head is larger than the diameter of the thread. This is the *gliding hole*. The hole in the opposite cortex is the *thread hole*. As the screw is tightened the two fragments are pressed together. **b** Both holes are *thread holes*. The fragments cannot be compressed. (From Müller et al. 1979)

matures and becomes organized, much of the newly laid-down woven bone around the screw is resorbed.

Screws may be either self-tapping or non-self-tapping. It was formerly thought that self-tapping screws provided a poorer hold in bone because they created more damage at the time of insertion and became embedded in fibrous tissue rather than in bone (Müller et al. 1979). This has been shown to be incorrect. The fibrous tissue forms as a result of instability and motion between the implant and bone. Instability is seen histologically as bone resorption and the formation of fibrous tissue, with occasional islands of cartilage and synovial-like cells (Schatzker et al. 1975a). Size for size, the different thread profiles of self-tapping and non-self-tapping screws have almost the same holding power. The advantage of the non-self-tapping screws is that they can be inserted into bone with far greater ease and precision, particularly when the screw comes to lie obliquely through thick cortex, which it often does when used to lag fragments. Self-tapping screws offer the advantage of speed and are best suited for the fixation of plates to bone.

In order to exert the most efficient degree of interfragmental compression, lag screws must be inserted into the center of fragments and at right angles to the fracture plane (Fig. 1.11). A single lag screw is never strong enough to achieve stable fixation of diaphyseal fragments. A minimum of two, and preferably three screws are required. This means that only long oblique and long spiral fractures can be stabilized with lag screws alone and only in short tubular bones such as phalanges, metacarpals, metatarsals, or malleoli. If lag screws alone are used for the fixation of long bones such as the femur or the humerus, they almost always end in early failure because of mechanical overload. Therefore, the most common use of lag screws in the fixation of shaft fractures is in combination with neutralization, buttress, or tension-band plates that protect the screw fixation from mechanical overload.

1.5.2 Lag Screw, Neutralization, and Buttressing

Neutralization plates or protection plates are used to protect the primary lag screw fixation. They conduct part or all of the forces from one fragment to the other. In this way they protect the fracture fixation from the forces of bending shear and rotation (Fig. 1.12).

In metaphyseal areas the cortex is very thin, and if subjected to load it can fail. Such failures result in deformity and axial overload of the joint. Therefore, internal fixation in metaphyseal areas requires protection with plates that support the underlying cortex. These are referred to as *buttress plates* (Fig. 1.13). Buttressing may also be achieved with external fixation.

1.5.3 Tension Band Plate and Compression Plate

Short oblique or transverse fractures do not lend themselves to lag screw fixation. In diaphyseal regions of the tibia and femur and occasionally the humerus, as will be seen in the section on splinting, we prefer intramedullary nailing for fixation. There are many transverse or short oblique fractures of diaphyses, such as of the radius and ulna, of the

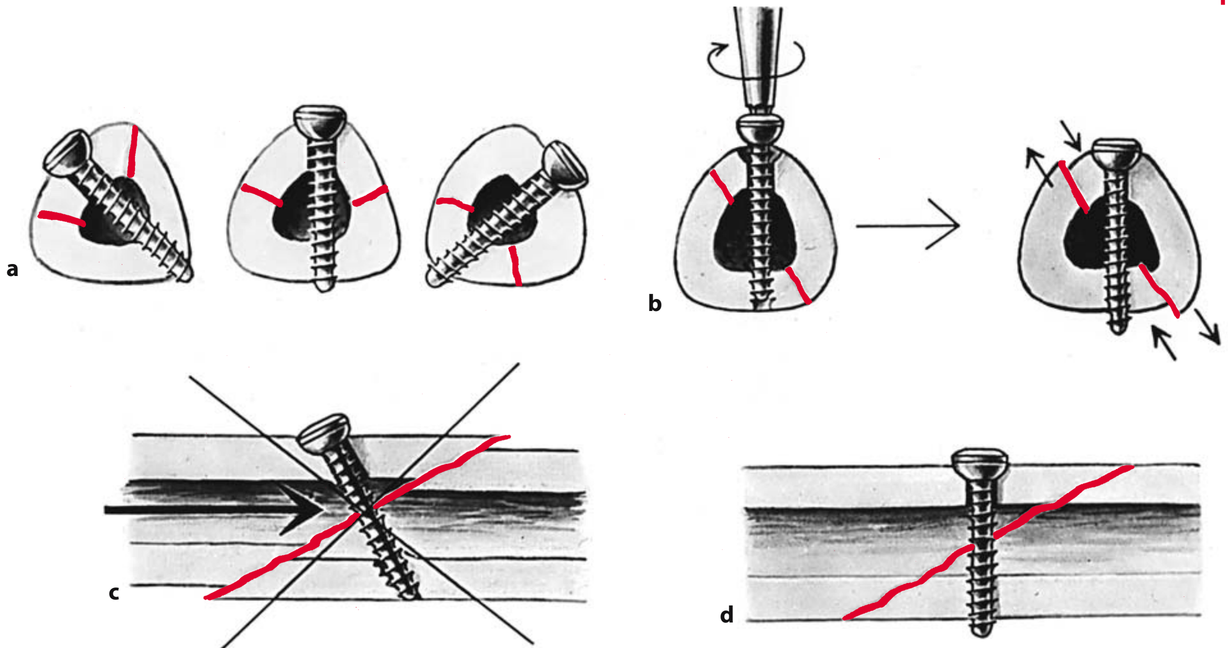


Fig. 1.11. a,b In order to exert the most efficient degree of compression, lag screws must be inserted into the center of the fragments and at right angles to the fracture plane. If they are off-center or angled, the fragments may displace on tightening of the screw, and reduction will be lost. **c** A lag screw inserted at a right angle to the fracture plane results in the best compression but does not provide the best stability under axial load, because the fragments may glide upon one another as the screw tips in the thread hole. **d** A lag screw at right angles to the long axis of the bone may cause tendency for the fragments to displace as the screw is tightened, but it provides the best resistance to displacement under axial load. Displacement can occur only if the thread rips out of the thread hole or the screw head sinks into the gliding hole. (From Müller et al. 1979)

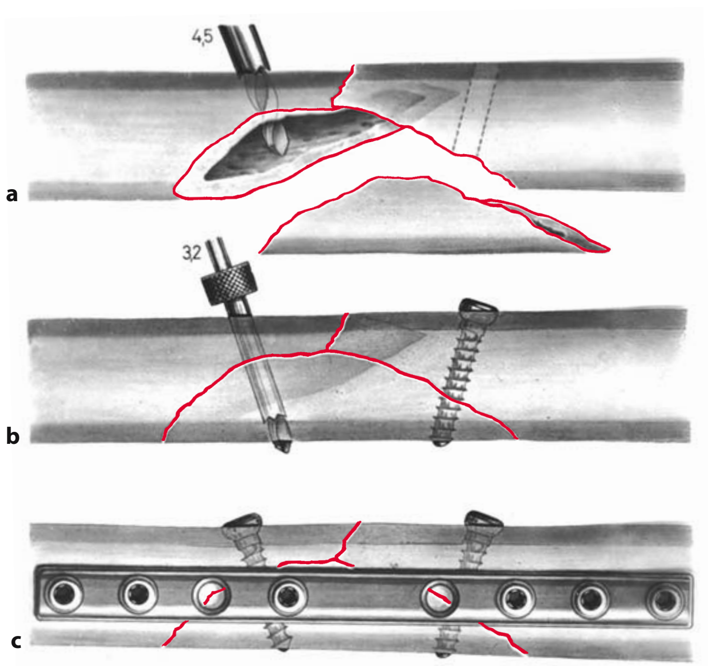


Fig. 1.12 a–c. The neutralization plate. The two lag screws provide interfragmental compression (**a,b**). The neutralization plate in **c** bridges the fracture zone and protects the lag screw fixation from bending and torsional forces. (From Müller et al. 1979)

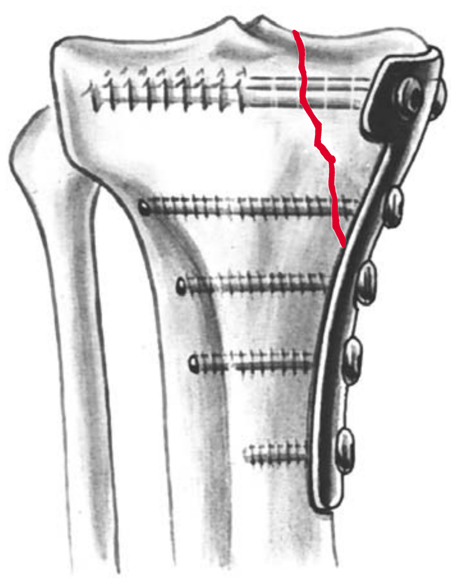


Fig. 1.13. The buttress plate. The T plate buttresses the cortex and prevents axial displacement. (From Müller et al. 1979)

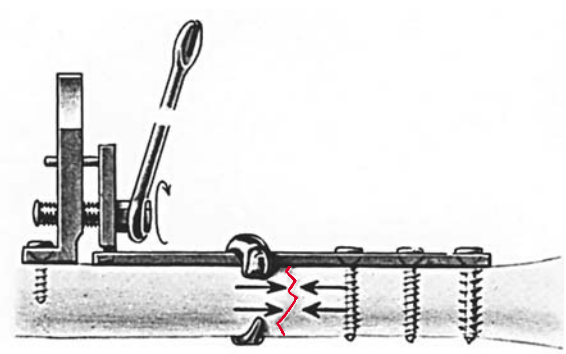
humerus, or of long bones close to or involving the metaphyses, which do not lend themselves to intramedullary nailing. Yet these fractures require stable fixation. Such fracture patterns can be stabilized by compression, but the compression has to be in the long axis of the bone. Such compression can be generated only by a plate. If a fracture is reduced and a plate is applied to the bone in such a way that axial compression is generated, either by means of the tension device or by the self-compressing principle of the dynamic compression (DC) plates or limited contact-dynamic compression plate (LC-DCP), the plate is referred to as a *compression plate* (Fig. 1.14a,b).

Certain bones such as the femur are eccentrically loaded. This results in one cortex being under compression and the other under tension (Müller et al. 1979; Schatzker et al. 1980). If a plate is applied to the tension side of a bone and placed under tension which causes the cortex under the plate to be compressed, such a plate not only achieves stability because of the axial compression it generates, but also, because of its location on the tension side of the bone, as bending forces are generated under load, it is capable of increasing the amount of axial compression. Such a plate is referred to as a *tension band plate* (Fig. 1.15).

1.6 Methods of Relative Stability or Splinting

1.6.1 External Skeletal Fixation

As we have seen from the classical experiments of Key (1932) and Charnley (1953), axial compression can be applied by means of pins which traverse bone and are then squeezed together. This type of fixation is stable over only a short length of the bone and only when broad, flat, cancellous surfaces are being compressed. When applied to tubular bone, such fixation is relatively unstable. Although not absolutely stable, the external fixator, either as a full frame or as a half frame, is extremely useful under certain clinical circumstances, such as in the treatment of open fractures not suitable for internal fixation, or in the treatment of infected fractures or infected nonunions or in the treatment of closed fractures of the end segment such as the distal radius, or when one wishes to delay the metaphyseal reconstruction because of the severity of the closed soft tissue injury. Under these circumstances the external fixator provides sufficient stability to permit functional


a

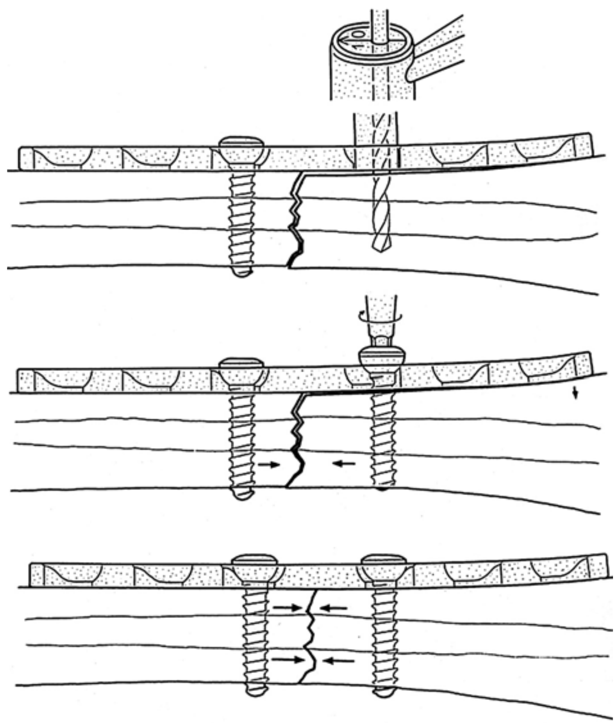

b

Fig. 1.14. a As the tension device is tightened, the plate is brought under tension and the bone under compression. (From Müller et al. 1979). **b** The dynamic compression plate. As the load screw is tightened it moves from its eccentric position to the center of the screw hole. This movement of screw and bone toward the fracture results in axial compression. (From Allgöwer et al. 1973)

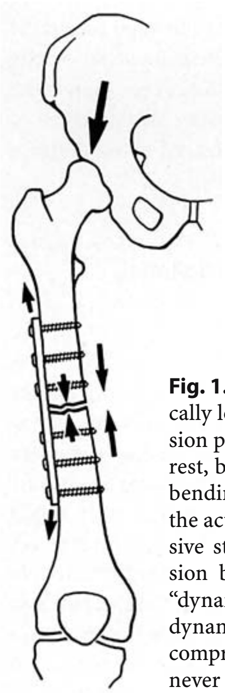


Fig. 1.15. Tension band plate. In an eccentrically loaded bone, not only does a compression plate secure a degree of compression at rest, but also, when the bone is loaded, the bending force so generated is converted by the action of the plate into further compressive stresses. Such a plate is called a "tension band plate" and the force generated "dynamic compression." The essence of dynamic compression is that although the compressive force fluctuates in magnitude it never reverses direction

use of the extremity while maintaining the bones in their reduced position. The stability is sufficient in fresh fractures to render the extremity painless and encourage soft tissue rehabilitation. Because external skeletal fixation does not result in absolute stability, it behaves similarly to unstable internal fixation in retarding or discouraging bone union. Therefore, when it is used as the definitive mode of fixation of open diaphyseal fractures it should almost always be combined with bone grafting. These statements are true for external fixators, which combine large pins with bars or tubes to form frames. Small wires under tension in combination with rings as employed by Ilizarov and many other surgeons provide much greater axial stability and are more successful as a definitive method of treatment, leading to union in situations in which large pins with bars or tubes would result in failure of healing without supplemental bone grafting.

1.6.2 Intramedullary Nailing

The manner in which an intramedullary nail splints and bestows stability is best likened to a tube within a tube. The nail is therefore dependent upon the length of contact with cortical bone for its resistance to bending and upon friction between the nail and bone and the interdigitation of fracture fragments for rotational stability. It is the contact with cortical bone that allows a nail to control angulation and translation. Intramedullary reaming is frequently employed to enlarge the area of contact between the endosteum and the nail. This enlarges the medullary canal sufficiently to permit the insertion of a nail which is not only large enough to provide stability but also strong enough to take over the function of the bone. Old small nails adapted to the size of the medullary canal were frequently limited in size to the diameter of the isthmus, which in young patients is frequently narrow. As a result, they were rarely strong enough and usually too flexible. Their use led to complications such as nail migration, nail bending, nail fracture, delayed union, and nonunion.

The biological expression of unstable fixation of viable fragments of bone is the formation of external callus. The instability associated with intramedullary nailing is reflected in the amount of callus produced. A large intramedullary nail may, when tightly wedged, provide sufficient stability to result in primary bone healing without discernible callus. Most often, however, a variable amount of periosteal callus is seen.

As a mode of fixation of weight-bearing extremities, intramedullary nailing has distinct advantages. Because it is a load-sharing device and much stronger than a plate, weight bearing can be resumed much earlier after intramedullary nailing than after other means of fixation.

Intramedullary nailing prior to the introduction of locking, because of the mode of application and the manner in which the nail rendered stability, was best suited for fractures in the middle one-third of the femur and of the tibia. The proximal and distal ends of tubular bones widen into broad segments of cancellous bone. In these areas the nail can provide neither angular nor rotational stability. Axial stability of a nailed fracture depends on cortical stability and on the ability of the cortex to withstand axial loads. Thus, certain fracture patterns were not ideally suited for intramedullary nailing. These were: long oblique and long spiral fractures, and comminuted fractures in which the cortex in contact was less than 50% of the diameter of the bone at that level.

An intramedullary nail has distinct mechanical and biological advantages. Because of its design and mode of application it is much stronger than a plate. Consequently, it will withstand loading for a much longer period of time than a plate before failure. Reaming combined with closed insertion of the nail without disturbing the soft tissues surrounding the fracture has been associated with a much more rapid and more abundant appearance of callus. Thus, it is an ideal device for tubular bones.

The limitations imposed on the conventional nail by the location of a fracture and its pattern have given rise to the development of the interlocking nail (Kempf et al. 1985). The first-generation interlocked nails greatly extended the indications for intramedullary nailing to fractures of the proximal and distal part of the diaphyseal segment of the femur and tibia. Certain fractures of the proximal femur, such as subtrochanteric fractures involving the lesser trochanter or associated with intertrochanteric fractures, could not be stabilized with the first-generation nails. This stimulated the development of the second-generation nails such as the reconstruction nail (Smith Nephew Memphis, TN, USA) or the short and long gamma nail (Howmedica) and more recently the PFM (proximal femoral nail; Synthes, Paioli, PA, USA).

For many years intramedullary reaming was considered an essential component of modern intramedullary nailing techniques because it not only improved the stability of the fixation, but, more importantly, surgeons were able to use larger nails, thus avoiding the complications of nail bending and breakage. A number of studies (Rhinelander 1973; Perren 1991; Waelchli-Suter 1980) demonstrated that reaming produces extensive damage to the endosteal blood supply of bone. The desire to use intramedullary nailing for the fixation of open fractures and recognizing the fact that dead bone would further infection led to the development of unreamed nails. Metallurgical and technical advances have overcome many of the early problems of bending and fracture with small-diameter nails. Recent experimental evidence that hollow nails appear to support infection has given rise to the development of solid unreamed nails for the femur and for the tibia (Synthes). The unreamed solid nail for the femur (Synthes) is a second-generation implant that embodies a number of very elegant proximal locking techniques.

1.6.3 Bridge Plating

Once reduction is achieved a fracture must be immobilized. The approach of the early AO/ASIF school in the treatment of a multifragmentary fracture was to secure stable fixation of each of the fragments (Fig. 1.16) and in this way convert the many pieces into a solid block of bone. The emphasis was on absolute stability, and primary union of bone was the object of an internal fixation. Because multifragmentary fractures united very slowly, it was mandatory to bone-graft them in order to prevent failure of the fixation with the resultant malunion or nonunion. Experience with closed locked intramedullary nailing strongly suggested that leaving the fragments alone preserved their blood supply and greatly accelerated their union.

Extramedullary splinting was tried with a plate (Heitemeyer and Hierholzer 1985). In this technique of plating the fracture is first reduced by means of indirect reduction. The zone of fragmentation is then bridged with a plate that is fixed to the proximal and distal main fragments. This maintains length, rotation, and axial alignment but reduction is not anatomical. This type of internal fixation is referred to as *bridge plating*. It is a form of splinting. It is not absolutely stable and union is by callus. Bridge plating is

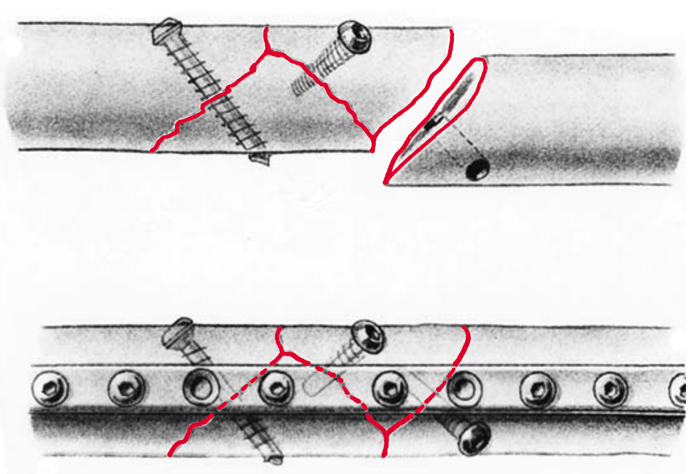


Fig. 1.16. In this manner of internal fixation each fragment is lagged to the other, converting the many pieces into a solid block of bone. The necessary stripping robs these fragments of their blood supply (from Müller et al. 1970, p56, Fig. 49c)

indicated only for the fixation of multifragmentary fractures. If one chooses to plate a simple transverse or oblique fracture, then absolute stability must be achieved by means of interfragmental compression, or excessive strain at the fracture site will likely cause failure.

In stable fixation of a multifragmentary fracture, union depends on the revascularization of the dead fragments. As a result union is slow and failure to bone-graft is the most common cause of failure of stable internal fixation. The bone graft is required to form a biological bridge opposite the plate and in this way protect the internal fixation. In bridge plating the union is rapid, and by callus. As a result the techniques of indirect reduction and bridge plating have made bone grafting of diaphyseal and metaphyseal multifragmentary fractures unnecessary. Bone grafting is now largely reserved for metaphyseal defects of articular fractures and for open fractures.

Not all fractures of long bones lend themselves to these techniques. Anatomical reduction of the diaphyses of the femur, of the tibia and of the humerus is not necessary. As long as length, rotation, and axial alignment are restored there will be no interference with function. The radius and the ulna are an exception. Pronation and supination and normal elbow and wrist function depend on the preservation of the normal anatomical shape and relationship of these two bones. Therefore anatomical reduction of these two bones is mandatory, and absolute stability of internal fixation is still the goal here. A multifragmentary fracture of the radius and ulna, despite the use of indirect reduction techniques, thus requires bone grafting to accelerate union.

1.6.4 Methods of Reduction

Direct reduction is the direct manipulation of bony fragments during an open reduction of a fracture. As a prerequisite, the fracture site must be exposed, which results in the stripping of soft tissue attachments and periosteum. The reduction is usually carried out with the help of surgical instruments such as levers and bone-holding clamps. It is a major cause of devitalization of bony fragments.

Indirect reduction is the reduction of a fracture by means of traction. In fractures that are being treated by closed methods, it is the principal method of securing reduction. Reduction of the fragments follows because of the application of an external force and because of the soft tissue attachments of the fragments. As traction is applied, the fragments tend to approximate themselves into reduction. Similar techniques have been adapted to open reduction in order to preserve the blood supply to the bony fragments and in order to simplify the reduction. Simple pull on a limb during an open reduction and the reduction of a fracture on a fracture table are classic examples of indirect reduction. The fragments are not manipulated directly, and their soft tissue attachment is not disturbed. As a result there is minimal interference with their blood supply.

Indirect reduction with the use of the distractor (Fig. 1.17) is a much more efficient technique because the distractor is fixed to the fragments being reduced. As a result the distraction is controlled and much less force is required. The distractor can be used alone to help in the reduction of a fracture (Fig. 1.18), as is most often the case in the reduction of diaphyseal

Fig. 1.17. The femoral distractor. This type will allow distraction, interlocking, and manipulation of the proximal and distal fragment of the femur in all planes. (From Mast et al. 1989)

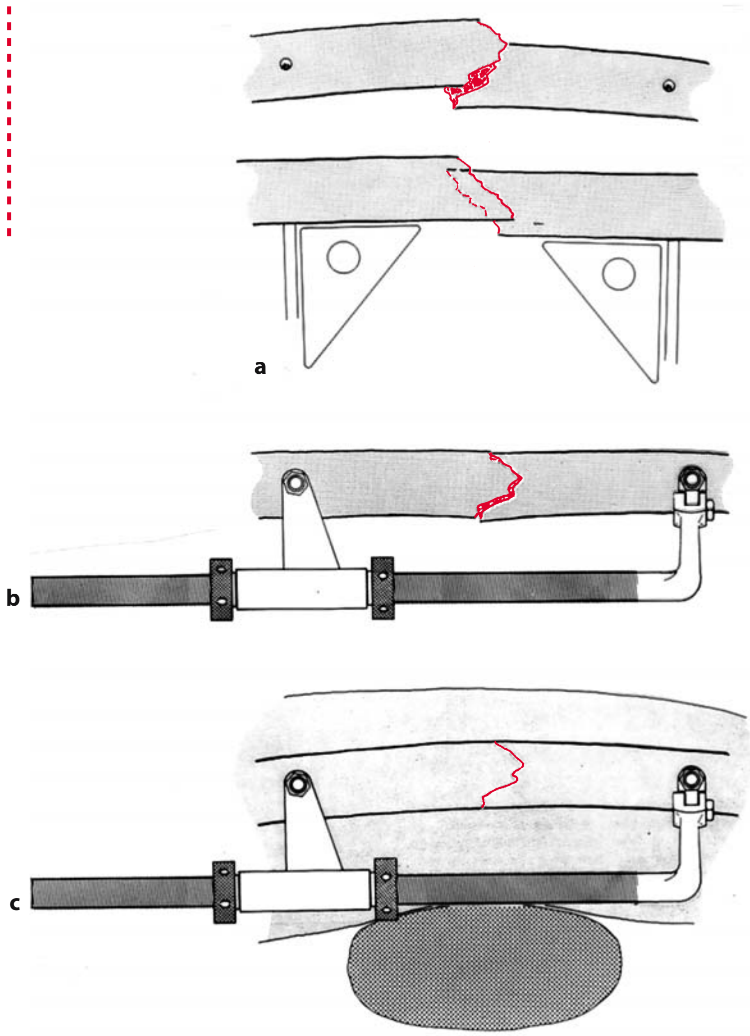


Fig. 1.18. a A simple fracture of the midshaft of the femur. Holes 4.5 mm in diameter are made in the proximal and distal fragments such that they will not interfere with the definitive implant after reduction. **b** With the femoral distractor attached, distraction of the fracture fragments is carried out. With distraction there is a tendency towards straightening of the femur and, if distraction forces are high, creating a deformity in the opposite direction from the distraction force – in this case a varus. **c** The tendency towards straightening may be corrected by carrying out the distraction over a bolster. The bolster acts as a fulcrum to maintain the antecurvatum of the femur. (From Müller et al. 1991)

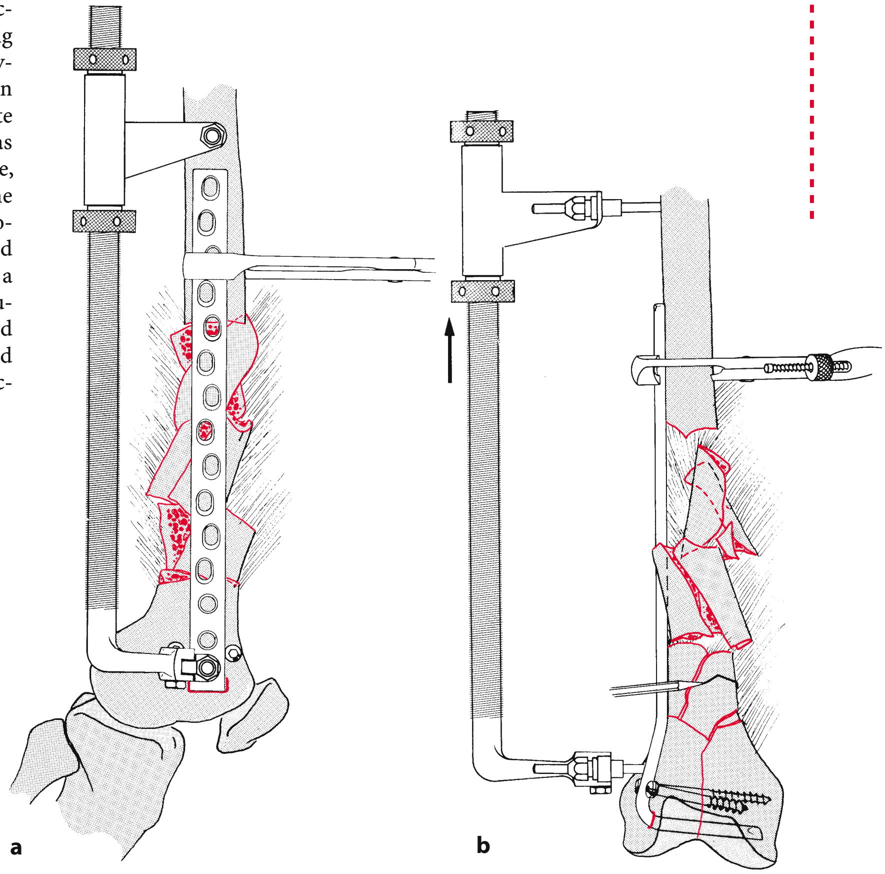
fractures, but also most effectively in combination with plates in the reduction of metaphyseal fractures such as supracondylar fractures of the femur (Fig. 1.19). One can also use the articulating tension device in its distracting mode to secure indirect reduction, but this first requires the fixation of a plate to one of the main fragments of a fracture (Fig. 1.20). Lastly, the implant itself can be used to secure reduction of a fracture. The classic example of this is the reamed intramedullary nail. As the nail fills the medullary canal it secures axial realignment of the fracture. A straight plate, when properly contoured, can also be used to secure reduction (Fig. 1.21).

Indirect reduction techniques are very important because they not only help to preserve the blood supply to bone, but also because they make the reduction easier and therefore safer. It must be kept in mind, however, that indirect reduction alone will not bring about union. Whether the fracture is simple or multifragmentary, preservation of the blood supply to fragments greatly aids in union, but in order to achieve union the correct mode of fixation must be chosen. As already outlined for simple fractures and articular fractures, absolute stability is required. For multifragmentary fractures, splinting by either a nail or a bridge plate is the method of choice.

1.7 Changes to the Early Concepts in Internal Fixation

At the time of the founding of the AO, the prevailing schools of fracture treatment, such as the schools of Sir Reginald Watson-Jones in Great Britain and Böhler in continental Europe, concentrated on bone union. In contrast the AO concentrated on *function*.

Fig. 1.19. a A severely comminuted fracture of the distal femoral shaft extending into the supracondylar and intracondylar area. The articular segment has been reconstructed and fixed. The blade plate has been inserted. The connecting bolt has been placed in the first hole of the plate, and the femoral distractor has spanned the comminuted area and portion of the femoral shaft to be plated. The plate is attached to the proximal fragment by means of a Verbrugge clamp. **b** Using a small instrument, such as a dental pick, comminuted fragments with their soft tissues attached are gently teased into approximate reduction. (From Mast et al. 1989)



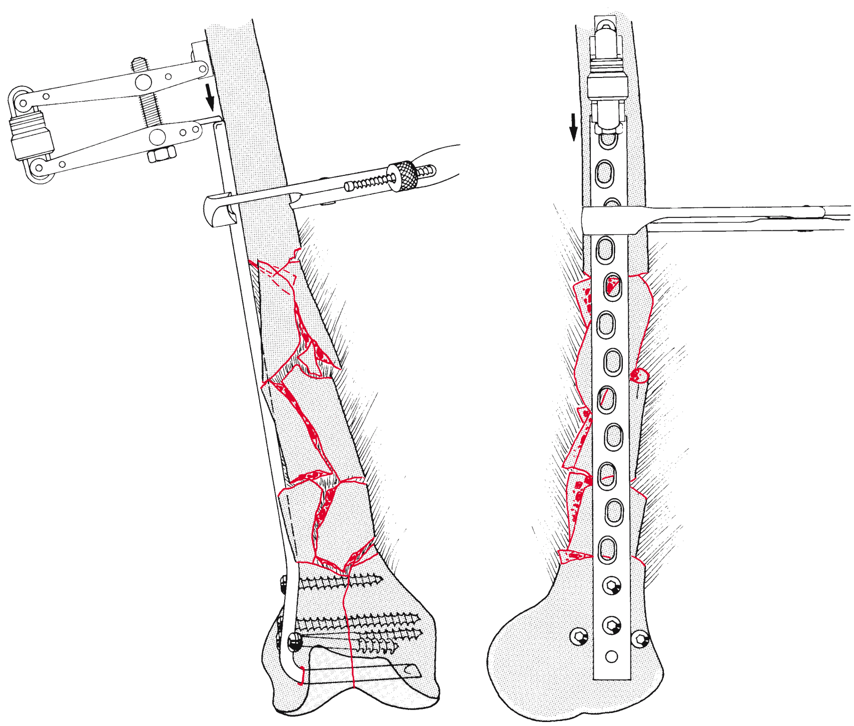


Fig. 1.20. The articulating tension device is placed as close as possible to the end of the plate and the tab turned to the distraction mode. The device is fastened to the bone by means of a uni- or bicortical screw, depending on the quality of the bone. Distraction is then carried out according to how much elongation of the segment is needed, determined in the preoperative plan. If the fracture morphology allows, the Verbrugge clamp may be tightened, the articulating tension device turned into compression mode, and an attempt made to load the fracture. It may be surprising, but by using pointed reduction clamps in a couple of key places, a comminuted fracture can be impacted and preloaded so that both mechanical stability and biological viability are achieved. Lag screws are inserted in the location previously occupied by clamps. However, in highly comminuted fractures this will be impossible, and a pure buttress function of the plate is all that can be realized. (From Mast et al. 1989)

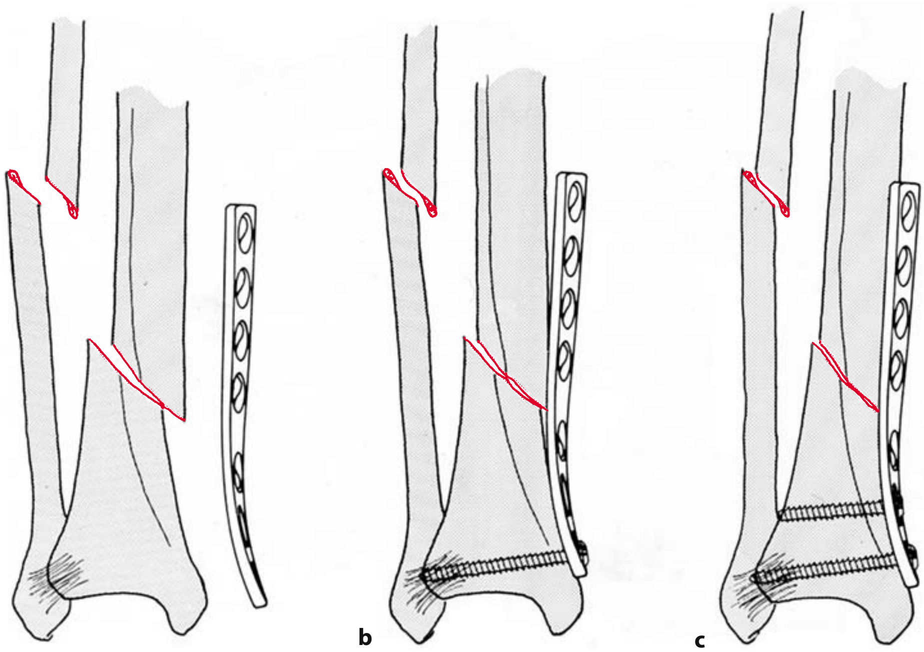


Fig. 1.21a–c. Reduction of a distal third oblique fracture using an antiglide plate. **a** Following surgical exposure, a seven- to ten-hole plate, depending on the fracture, is selected. It is first twisted so that there is a torsion in the plate of approx. 25°, then it is placed in a bending press and a mild concavity is pressed into its distal two-thirds. This may be checked at surgery by using a marking pencil and a 20-cm length of suture thread to draw an arc on a flat surface against which the curve of the plate can be checked. The curvature may also be ascertained by a comparison AP X-ray of the opposite side. **b** The plate is then fixed to the distal fragment at the level of the buttress of the medial malleolus with one screw. Care must be taken not to enter the joint with the screw because it is so low and because the curve of the plate has the natural tendency to direct the screw into the joint. There the normal 3.2-mm drill guide is used and a screw is inserted parallel with the joint. The screw is snugged but not definitively tightened. The plate is then rotated around the distal screw until its original orientation to the distal fragment is correct in the sagittal plane. The fit of the plate against the proximal fragment will be a little tight at this point. To accommodate this, the distal screw may need to be loosened slightly The tightness of the proximal end of the plate against the proximal fragment represents the plate-bone interference that in the end will reduce the fracture. With only the distal screw in place, the alignment of the fractures will be improved. At this time rotation should be corrected by gently twisting the patient's foot, and therefore the distal fragment, in the appropriate direction. **c** When little or no shortening is present, the next screw hole is drilled through the plate with a neutral drill guide. The screw length, which will be a little greater because the plate is not yet positioned snugly against the bone, is measured and the screw is tapped and inserted. The distal screw and the second screw are then tightened together, but not definitively. The distal fragment of the fractured bone will be drawn in toward the plate. (From Mast et al. 1989)

The AO group felt that immobilization resulted in *plaster disease* which was characterized by atrophy of the soft tissues, severe osteoporosis, thinning of articular cartilage, severe joint stiffness, and causalgic pain. To fight this disease the AO introduced "functional rehabilitation," a concept of fracture care based on the fact that if one achieved absolutely stable fixation of a fracture, then fracture pain would be completely abolished. This made it possible for the patient to move the extremity almost immediately after surgery and commence rehabilitation while the fracture was healing.

This type of fracture treatment required the reduction to be anatomical and the fixation of the fracture not only sufficiently stable to abolish all pain, but also sufficiently strong and lasting to allow functional use without the danger of nonunion or malunion.

Stability of the fixation was achieved by *compression*, which recreated the structural continuity of the bone. The lag screw became the building block of stable internal fixation, and where necessary it was combined with *protection* or *neutralization plates or buttress plates.* Simple transverse or oblique fractures, because they could not be stabilized by means of lag screws, were brought under axial compression by means of *compression plates*. The emphasis in fracture treatment was on *mechanical stability*, and the goal of internal fixation was to take many pieces of bone and convert them into a single solid block.

Simple fractures of the mid-diaphysis of long bones such as the femur and tibia could also be treated by intramedullary nailing. Although this form of treatment, called *splinting*, achieved sufficient stability to allow functional aftertreatment, it did not provide absolute immobilization of fragments, which therefore healed with callus. In contrast, bone immobilized by means of interfragmental compression, and therefore stable, healed without the radiological evidence of callus by what was referred to as *primary bone union*.

Bone grafts were used frequently to ensure union of plated multifragmentary fractures and to fill defects in both cortical and metaphyseal bone. Indeed, failure to bone-graft was the most frequent cause of failure of an internal fixation.

More than 40 years have passed since the formulation of the initial AO principles and methods. The initial goals of the AO – the improvement of fracture care with emphasis on the return of full function – have remained the same. There have been major changes, however, in principles, techniques, and implants. The most significant change has been a shift of emphasis from the mechanical to the biological aspects of internal fixation, with great emphasis on the preservation of the blood supply of bone and of soft tissue. This has led to the development of new methods of surgical reduction, approaches, and exposure, and methods of stabilization. The recently developed minimally invasive approaches with specially designed and developed techniques and implants to achieve fixation, which fall under the acronym of MIPO (minimally invasive plate osteosynthesis), are an example.

Paralleling these changes at a more fundamental level has been the recognition that only living bone is capable of overcoming motion at the fracture by the formation of callus which then leads to union. This has led to a rational approach in the choice of treatment methods. If the bone is alive, then splinting methods such as bridge plating and intramedullary nailing, which provides only relative stability, will lead to rapid union with abundant and strong callus. If on the other hand blood supply and other biological factors have been compromised as in an open fracture, then if one chooses splinting, or even absolutely stable fixation, a bone graft is likely to be required to facilitate and accelerate union. If in contrast one is dealing with a fracture situation where one or more fragments are necrotic, then one must choose absolutely stable fixation in order to achieve union. A fracture of the proximal pole of the scaphoid is a good example. Methods of relative stability in the presence of bone necrosis result in non-union. Under conditions of absolute stability such as with lag screw fixation, union takes place thorough a process called primary bone union. In this type of union the dead bone stimulates in the adjacent living bone a proliferation of capillary buds which form the so-called cutting cones. These grow from the living bone into the dead bone, forming new osteons that not only bridge the fracture but eventually also lead to revascularization of the dead bone fragment. Primary bone union in reality is the remodeling of dead bone in the presence of absolute stability at the fracture. Such union is much slower than union with the formation of callus, and the revascularization of the bone fragments is even slower. This must be kept in mind when removal of fixation devices is being considered. Devices used to provide absolute stability should not be removed from large tubular bones in less than two years, even though the bone may have the radiological appearance of having remodeled completely. Premature removal results in refractures. The appreciation of these fundamental differences is the key to choosing the correct technique of internal fixation of a fracture. This applies also to the treatment of articular fractures.

1.7.1 Articular Fractures

In the 1960s and 1970s, the principles of internal fixation and stability were the same for articular fractures and for fractures of the diaphysis. In the years to follow we came to appreciate that the mechanical and biological requirements of articular and diaphyseal fractures are different. This has led to major alterations in the principles and methods of their treatment.

The principles of articular fracture surgery –

- Atraumatic anatomical reduction of the articular surface
- Stable fixation of the articular fragments
- Correction of axial deformity
- Metaphyseal reconstruction with bone grafting of defects
- Buttressing of the metaphysis
- Early motion
- still apply today. What has changed is the timing of the different steps of the metaphyseal reconstruction.

Articular reconstruction must be undertaken as early as possible and with the least trauma to the tissues. A delay leads to permanent deformity because articular fragments unite rapidly and defy late attempts at reduction. The nature of the intraarticular fracture is a factor to consider. A simple articular fracture can be taken apart and reduced even at 6 weeks. A multifragmentary articular fracture with impaction of the fragments already at 4 weeks may defy attempts at reduction. Articular cartilage does not remodel. Any residual incongruity becomes permanent and can lead to post-traumatic arthritis (Llinas 1993, 1994). In contrast, the diaphysis and metaphysis have tremendous capacity for remodeling. Furthermore, any residual deformity can be relatively easily corrected by osteotomy.

The preservation of the viability and integrity of the soft tissue envelope of the metaphysis is the key to success (Marsh and Smith 1994; Stamer 1994). Thus, external fixation is frequently used as a temporary measure to achieve length and alignment of the metaphysis while the soft tissue envelope is recovering. The definitive reconstruction is then delayed for 2–3 weeks or longer if necessary. If the articular fragment is small and does not afford purchase for the external fixator, the joint is bridged temporarily with the external fixator to provide the necessary immobilization. Whenever the definitive reconstruction is carried out, either as a primary or delayed procedure, all measures are taken to minimize the damage to the blood supply of the soft tissue and bone. These measures include indirect reduction, minimal exposure, and percutaneous screw fixation of fragments. Buttressing continues to be important in preventing axial deformity, but the methods of buttressing today are designed to minimize soft tissue trauma. Thus, buttressing today may be in the form of plating or it may be achieved by means of an external fixation frame or it may be a combination of both. These principles which we have followed for many years constitute today the core of the treatment protocols of most major trauma centers.

1.7.2 Diaphyseal Fractures

As already alluded to above under general considerations of the changes to the early concepts, the most notable change in the principles and methods of treatment of fractures has been in the handling of diaphyseal injuries. The shift has been from what one might call the mechanical era during which emphasis was on the mechanical aspects of internal fixation, with absolute stability and primary bone union as the goals, to the biological era, with emphasis on the biological aspects of internal fixation with splinting, relative stability, and healing with callus as the preferred method. Today the dominant theme in the fixation of diaphyseal fractures of long bones is the status of the soft tissue envelope combined with the biology of bone and the preservation of the blood supply to bony fragments. Absolute stability is no longer the object of internal fixation.

1.7.2.1 Locked Intramedullary Nailing

Whereas at one time the lag screw and plates were the building blocks of stable internal fixation of fractures of the diaphysis, today the *locked intramedullary nail* has become the choice implant for the fixation of diaphyseal fractures of major long bones. The development of locking of the main fragments onto the nail has greatly increased the scope of intramedullary nailing. Whereas before, multifragmentary fractures were a contraindication, today a multifragmentary fracture is *the* indication for using a locked intramedullary nail. Locking has also made it possible to stabilize fractures of the proximal and distal third of the diaphysis and to treat subtrochanteric fractures with involvement of the lesser trochanter and ipsilateral fractures of the shaft and neck of the femur (Kyle 1994).

1.7.2.2 Reaming

The biological and mechanical events associated with reaming or nail insertion and the consequent cardiopulmonary events have become the subject of major controversy among trauma surgeons. Reaming has been recognized as contributing significantly to the damage of the blood supply to the cortex. Reaming has also been recognized to cause a marked increase in the intramedullary pressure of bone (Stürmer 1993) and in a marked rise in the associated embolization of marrow contents to the lung (Wenda et al. 1993). These observations have resulted in the development of unreamed intramedullary nails for the tibia and femur, which as one might expect have not eliminated the cardiopulmonary events. In recent years we have witnessed a lively debate as to whether one should nail the long bone fractures of polytrauma patients with a high Injury Severity Score, who have been in shock, and who have concomitant injuries to the thoracic cage and lung contusion (Pape et al. 1993). Many studies completed during and since the peak of this controversy have shown that the presence of a lung contusion is by far the deciding factor as to whether cardio-pulmonary complications are likely to develop. Each patient and each particular problem must be evaluated on its merits. The intramedullary nailing of a single extremity in most cases will not constitute a problem. However, if more than one bone must be nailed in a patient with the risk factors enumerated above, then it is preferable to stabilize the fractures in these patients either definitively with plates or by means of temporary external fixator (O. Trentz, personal communication) with conversion to definitive intramedullary nailing when the condition of the patient has stabilized.

Although locked intramedullary nailing is the preferred method for internal fixation of diaphyseal fractures, there continue to be indications for plating. These will be discussed in detail in the ensuing chapters. Whenever plating is carried out, the surgeon has the choice of carrying out either a direct or an indirect reduction. Direct reduction is the major cause of the devitalization of bony fragments. *Indirect reduction* techniques have been popularized to minimize the damage to the blood supply of bone and of the soft tissue envelope (Mast et al. 1989). The method of reduction does not determine the degree of stability. Although stable fixation is usually practiced in association with direct reduction, indirect reduction techniques are equally applicable.

1.7.2.3 Bridge Plating

The method of *bridge plating* (Heitemeyer and Hierholzer 1985) was developed to help prevent the devitalization of fragments of multifragmentary fractures (Perren 1991). In this technique of plating the fracture is first reduced by means of indirect reduction in order to minimize the devitalization of fragments, as bridge plating is very dependent on the viability of bone for the formation of callus and union. In this technique, once length and rotation are reestablished, the zone of fragmentation is bridged with a plate that is fixed to the proximal and distal main fragments. The correct contouring of the plate reestablishes correct alignment. This type of internal fixation is a form of splinting. It is not absolutely stable, and union is by callus. This technique of plating is indicated only for the fixation of multifragmentary fractures. If the surgeon chooses to plate a simple transverse or oblique fracture, then absolute stability must be achieved by means of interfragmental compression, or excessive strain at the fracture site is likely to cause failure (Perren 1991).

The techniques of indirect reduction and bridge plating have made bone grafting of diaphyseal and metaphyseal multifragmentary fractures unnecessary. Bone grafting is now largely reserved for metaphyseal defects of articular fractures and for open fractures.

Anatomical reduction of the diaphyses of the femur, of the tibia, and of the humerus is not necessary. As long as length, rotation, and axial alignment are restored there will be no interference with function. The radius and the ulna are an exception. Pronation and supination and normal elbow and wrist function depend on the preservation of the normal anatomical shape and relationship of these two bones and fractures of these two bones. They are not unlike articular fractures. Therefore anatomical reduction of these two bones is mandatory, and stability should be achieved with an appropriate plating technique.

1.7.2.4 Blood Supply to Bone and Implants

Preservation of the blood supply of the bony fragments has been achieved not only by indirect reduction and by changing the methods of internal fixation, but also by changes in the design of implants. The unreamed intramedullary nail was developed to minimize the damage to the endosteal blood supply of long bones. The observations of Perren (1991; see also Gunst et al. 1979; Waelchli-Suter 1980), who studied the effects of plating on the blood supply of bone, led to the discovery that the porosis of the cortex beneath the plates was not the result of stress protection but rather the result of local bone necrosis and its accelerated haversian remodeling. The degree of necrosis was determined by the degree of contact that the plate made with bone. This explained the seeming paradox that the so called haversian remodeling was greater, with flexible and elastic plates which were being used to overcome the stress protection of the stiffer metallic plates. The flexible plates made closer contact with the bone and interfered to a greater degree with the blood supply of the underlying cortex.

1.7.2.5 The Limited Contact-Dynamic Compression Plate (LC-DCP)

These observations have led to the development of plates that have been designed in such a way as to minimize their contact with the underlying bone. The limited contact-dynamic compression plate (LC-DCP) is an example of such a plate (Fig. 1.22).

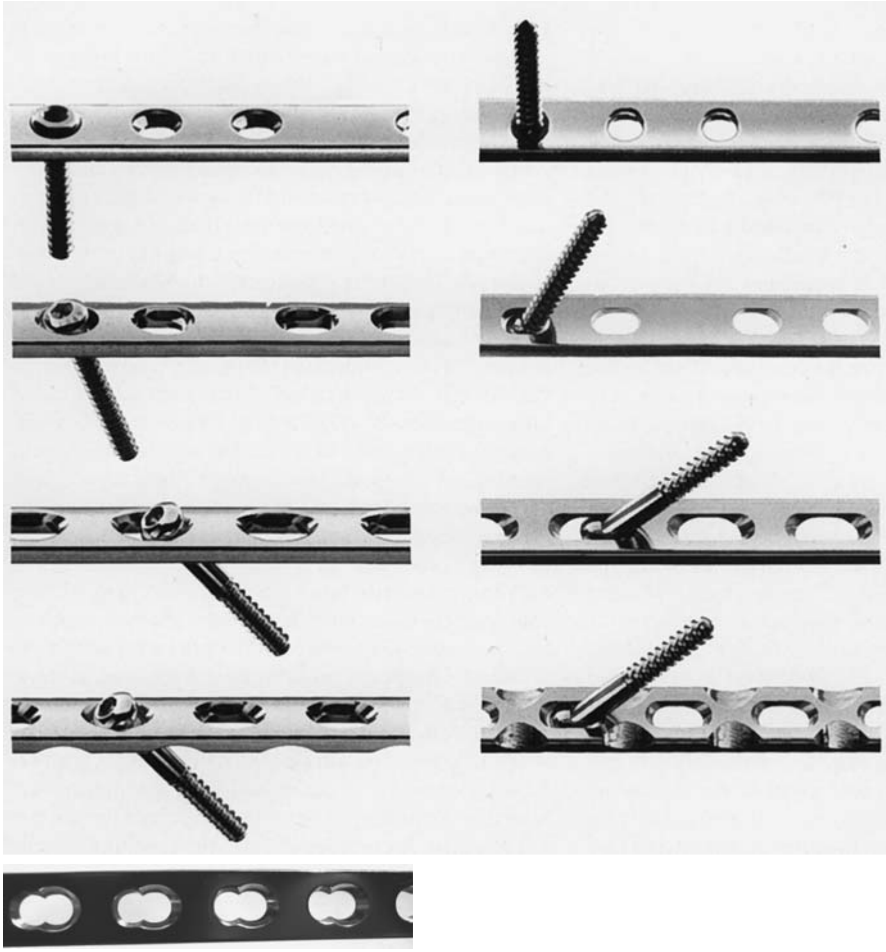


Fig. 1.22a–e. The developments in AO internal fixation plates. In **a–d,** upper *(left)* and lower *(right)* surfaces are shown. **a** The round hole plate (Müller et al. 1963). The conically undercut screw head allows for only a perpendicular position of the screw. The distance between the inner screw holes is larger. The plate undersurface is smooth. **b** The dynamic compression plate (DCP; Perren et al. 1969). The spherical contact geometry allows for 20° tilting of the screw along the long axis of the bone. **c** The dynamic compression unit (DCU; Klaue and Perren 1982). The completely symmetric screw holes are distributed at even distances throughout the plate. Symmetric screw holes with oblique undercut for improved range of inclination. **d** The limited-contact dynamic compression plate (LC-DCP; Perren et al. 1969) viewed from above; symmetric arrangement of the screw holes without a solid elongation between the innermost screw holes. The screw holes themselves are symmetric and are provided with two sloped cylinders. Lateral undercuts allow for bone formation at the plate (tension) side of the periosteal surface. Less damage to blood supply results, and the trapezoid cross-section allows for easier and less traumatic removal of the plate. (From Müller et al. 1991). **e** The combi (combination) hole permits the insertion of a fixation screw through that portion which is identical to the screw hole in an LC-DCP plate. The threaded portion is designed to lock the screw head and provide "locked" angularly stable fixation.

1.7.2.6
The PC Fix or the Point Contact Plate (PCP) and Angularly Stable Fixation

In conventional plating, the stability of plate fixation is dependent on the degree of compression between the plate and the bone and on the interdigitation of the bony fragments and their interfragmental compression. To achieve maximum friction and compression between the plate and bone, the screws must be tightened to the maximum possible. The moment a screw loosens, the compression between the plate and underlying bone is lost and the degree of fixation drops dramatically.

The development of the LC-DCP was an attempt to limit the contact of the plate with the underlying bone and thus limit the damage to the periosteal blood supply. Beyond this, the LC-DCP functioned similarly to all conventional plates.

To avoid any contact between the plate and bone and thus decrease even further any damage to the blood supply of bone derived from soft tissue, Perren and Buchanan (1995) developed the PCP (point contact plate) or PC Fix (point contact fixator). The PCP functions like an external fixator applied internally.

The key to this is the fact that the screw heads are very securely fixed to the plate, just as the Schanz screws are fixed to the tubes of the tubular fixator. This made it possible for this new plate to have no contact with the underlying bone. The transmission of forces is from bone to screw to plate, and not from bone to plate. The PC Fix is anchored to the bone with unicortical screws that are self-drilling and self-tapping. The head of the screw is conical in shape and fitted out with a thread. The screw hole of the plate has an identical profile and is also threaded, which makes the heads self-centering. Upon insertion the screw head threads itself into the plate to become one. Although the PC Fix underwent extensive clinical trials, it never came into general clinical use. The advantages of locked fixation were first explored in spine surgery and then in fracture surgery in the LISS (limited internal stabilization system), which was developed specifically to exploit all the advantages of minimally invasive surgery combined with angular stability. Today because of the enormous advantages of angular stable fixation, the AO Foundation and its commercial partner Synthes Inc. have extended the principle of locked plate fixation to all plates. This was made possible through the development of the "combi hole" for plate fixation (see Fig. 1.22e). The combi hole has replaced the screw holes developed for the DCP and the LC-DCP. The combi hole is shaped like a figure-eight. The end further away from the middle of the plate retains all the features of the old DCP hole, which allows the insertion of screws either eccentrically in the "load position" to achieve axial compression or in the "neutral position" for fixation of the plate to bone. The end of the hole closer to the middle of the plate is threaded. The pitch of the thread and shape of the hole mirror those of the head of the screw, and the pitch of the thread is the same as that of the screw thread used for the attachment of the plate to bone. When the threaded conically shaped screw head engages in the threaded hole, it locks when tightened. This fixation of the screw to the plate creates an angularly stable construct. The fixation of the plate to bone no longer depends on compression between the plate and the underlying bone, but simply on the holding power of the screws in bone. Because the screws are fixed to the plate, all the screws act in unison when subjected to a bending force, whereas in conventional plating each screw acts alone. Since all the screws act in unison they provide vastly superior holding power in bone because of a much larger segment of bone providing the fixation.

1.7.2.7 The Advantages of Locked Fixation and Its Angular Stability

Sparing of Periosteal Blood Supply

Since in the locked compression plate (LCP) the fixation which the plate provides does not depend on the compression between the plate and the bone but rather depends on the fixation of the screw to the plate and the anchorage of the screw in the bone, the plate no longer needs to make any contact with the underlying bone. The immediate advantage of this is that there is absolutely no interference with the periosteal blood supply.

No Need to Contour the Plate

Another advantage is that the plate no longer needs to fit exactly to the shape of the underlying bone. Thus a plate no longer needs to be carefully contoured. It is simply held in place as the screws are inserted.

Improved Holding Power

Because the screw is locked to the plate, it is angularly stable. In a conventional plating the moment the screw loosens and backs out ever so slightly, fixation begins to fail and displacement can take place, which sets up a vicious irreversible cycle leading to greater and greater loss of fixation. With a screw that is locked to the plate, this loss of fixation is not possible. The only way displacement can take place is for the anchorage of all of the screws in the bone to fail simultaneously. Unlike conventional screws where the holding power of each screw is dependent on its own pull-out strength, in locked fixation where the screws are fixed to the plate, the screws act in concert and the holding power is additive with all the screws acting together. In conventional plating when failure under bending begins to occur, there is failure of the first screw subjected to a pull-out force, followed then by the second screw and so on. Where all the screw heads are locked to the plate, under a bending force that is tending to pull the screws out of bone, the load is shared by all of the screws, since the pull-out load is equally transmitted to all of them. The result is a much greater holding power. The advantages of this are several. First of all, because the holding power is a summation of the screws together, the locked type of plate fixation offers much better and stronger fixation. Hence it is superior in providing fixation of fractures in osteoporotic bone. Because the holding power is greater, there is no need for bicortical screw purchase. Unicortical screw engagement is sufficient. One caveat which applies here and which must be remembered since in practice it has contributed fairly commonly as a cause of failure is that because the bone is tubular the only time unicortical fixation is at its optimum is when the screw is at 90° to the tangent at its point of entry. As the direction of the screws is determined by the attitude of the plate, the alignment of the plate at the start of the fixation is also crucial. The plate must be in the middle of the cortex, and its tilt must be such that the screws are directed at 90° to the tangent at their point of entry.

Self-Drilling and Self-Tapping Screws

The advantage of unicortical screws is that they can be made self-drilling and self-tapping, and if one limits the length of the screws to slightly greater than the thickness of the cortex, one can do away with the measurements of screw length. From the foregoing one can readily see that the use of a locked plating has decided advantages. The one prerequisite to successful application of locked internal fixation which often presents considerable clinical difficulties is that the fracture must be reduced and must be maintained as reduced when the plate is applied. Unlike conventional plating, where the plate imparts its shape to the underlying bone (a principle often invoked in using the plate to secure reduction), in locked plating, whatever the position of the bone when the screws are inserted, that is the position which remains. In order to increase the holding power of the screws in cancellous bone, one not only uses bicortical screws which require predrilling of their hole, but the direction of the individual screws can be altered. Their 'misalignment,' so to speak, greatly increases their holding power in cancellous bone and conversely in osteoporotic cancellous metaphyses.

Locked Angular Fixation and Bone Healing

In using this type of fixation there are certain mechanical aspects that must be considered. In a fracture under load, because of the discontinuity of stiffness, the fracture is the focus where maximum deformation of tissues occurs. Hence under loading it is the site of maximum strain. Bone tissue is brittle, with a very low strain tolerance. Thus bone cannot bridge a fracture gap during healing as long as deformation is taking place. Hence the formation of callus, a tissue with graduated strain tolerance in which the tissues are arranged in accordance with the strain they are subjected to and one they can tolerate. On a relative scale, the strain tolerance of fibrous tissue is 100; that of cartilage is 10, and that of bone, 2. During healing the deformation of callus is gradually reduced through increasing stiffness, the result of differentiation of tissue into cartilage. The cartilage matrix then degenerates, mineralizes, becomes invaded by blood vessels, and is eventually changed for bone, a process known as endochondral ossification.

As previously explained, the so called primary bone healing under conditions of absolute stability achieved with compression takes place only if the interfragmental strain in the fracture zone is near zero, because bone tissue is brittle and cannot bridge a fracture during healing as long as deformation is taking place. Induction of callus under such conditions is minimal. In the early days of AO it was thought that pain-free mobilization was only possible under conditions of absolute stability. However, experience with intramedullary nailing and bridge plating showed that relative stability also allows pain-free mobilization. Relative stability must allow also the induction of callus formation. Elasticity of the fixation is a precondition for the induction of callus formation. Thus deformability of the implant is the key. A screw is relatively rigid compared to bone. Under peak load which exceeds the strength of bone, the screw will lose its anchorage and become irreversibly loose. Bridge plates, intramedullary nails, and external fixators are splints that under peak load bend elastically. Locked plates and external fixators will undergo plastic deformation under extreme load as long as this load does not exceed the holding power of their anchorage in bone.

The clinical problem encountered with the PCP or PC Fix was that the technique employed still required an open reduction of the fracture. The decided advantages of closed techniques, which entail minimal exposure and no exposure of the zone of injury, the so called biological plating techniques, stimulated further development of implants which combined the advantages of locked plate fixation with minimally invasive techniques, particularly for those areas which do not lend themselves to intramedullary nail fixation.

The first device to appear was the LISS (limited internal stabilization system; Frigg et al. 2001; Fig. 17.22a–d). The LISS is an ingenious device that makes full use of the locked internal fixator concept. The shape of the LISS was chosen to fit best the greatest number of femora. Because of a bow built into the design to mimic the physiological bow of the femur, the device has a right and a left side. Distally the LISS flares and is fixed to the femur with longer self-tapping screws that lock in the plate. Proximally in the diaphyseal portion, the LISS is fixed to the bone with unicortical self-drilling and -tapping screws that also lock in the plate. The screw heads have a threaded conical profile, which provides stable angular fixation of the screw-fixator junction; the screws are self-centering in the hole. There is also "the puller," a provision made to be able to bring the proximal shaft closer to the plate and correct the frequent valgus malalignment which arises during the insertion of the device. The LISS also has an insertion handle that is securely fixed to the plate prior to insertion. This ingenious device is used first to guide the plate into position, and then when the plate is in position it serves as a guide for the insertion of the fixation screws.

The major shortcoming of the LISS is that it requires the femur to be reduced prior to the fixation of the plate to the bone. The screws lock in the plate and maintain the bone in the "position of reduction" achieved by the surgeon. The angular stability of the system greatly enhances the holding power of its screws in bone and makes it most attractive also for the fixation of supracondylar fractures in osteoporotic bone, which have time and again defied the skills of the surgeon because of the failure of fixation devices.

Further developments in the implant design and manufacture have led Synthes Inc. to the extension of locked internal fixation to all small-fragment and large-fragment plates. These plates, now referred to as LCPs (locked compression plates) have also been fitted with a further refinement – the "combination hole" which allows the surgeon when using these plates to choose between locked internal fixation, conventional fixation, or a combination of both techniques. In addition to the modification of existing plate designs to LCP, there has also been the development of plates for special anatomical regions such as the Philos plate for the proximal humerus, special periarticular plates for the proximal and distal tibia, the LCP (locked condylar plate) for the distal femur, a LISS plate for the tibia, and special plates for the upper extremity. All these devices have been developed under the auspices of the AO-ASIF Foundation and are sold under the trademark "Synthes".

1.8 Biological Plating and Minimally Invasive Plate Osteosynthesis (MIPO)

During the early years of the AO school of operative treatment of fractures, form and function were considered to be inextricably linked. Hence the dictum of the AO of anatomical reduction as a prerequisite for the return of function. The AO pioneers also thought that only absolute stability would render extremities sufficiently painless to permit early motion, which was recognized as essential in the recovery of function. Hence in the treatment of fractures all efforts were directed to the achievement of absolute stability. Absolutely stable fixation led to bone union without radiologically discernible callus. This type of union was called "primary bone healing," and primary bone healing became the goal of treatment whenever one attempted an internal fixation. Callus was considered a sign of instability; it was bad, a danger signal, and a signal of impending failure. Anatomical reduction was also considered important in restoring the inherent structural stability of bone. Compression by means of lag screw fixation or axial compression by means of compression plates became the foundation of absolutely stable fixation. When dealing with multifragmentary fractures all efforts were made to convert the many pieces into a solid block of bone (see Fig. 16.5). The achievement of mechanical stability was of paramount importance. The atraumatic handling of soft tissue was considered important to prevent infection but was not considered an important factor in securing bone healing. Blood supply of bone hovered in the background as a factor of much lesser importance than stability. It was recognized that the absence or interference of blood supply delayed healing and risked failure because of mechanical breakdown of the fixation. Hence the dictum to bone-graft all multifragmentary fractures in order to hasten the formation of a bony bridge which would then protect the mechanical fixation. The bone once united would then gradually revascularize and remodel. Osteoporosis was seen in association with plating but was initially thought to be the result of mechanical shielding of the bone from physical stresses, and was referred to as "stress protection." Intramedullary nailing was recognized as a good form of treatment of simple fractures of the mid-diaphysis of femur and tibia. It was recognized as a form of relatively stable form of fixation, a form of splinting. Callus was recognized as a means of union of bony fragments when stability was not absolute. It was also recognized that such healing was stronger and mimicked the type of union that occurred when fractures were treated closed without surgical intervention. However, intramedullary nailing, because of its inherent mechanical limitations, played a limited role as a form of fracture fixation.

Locked intramedullary nailing and its very obvious advantages are responsible for the shift from the mechanical approach in fracture treatment to what is referred to as the biological approach or biological internal fixation. Locked intramedullary nailing is a closed technique. The fracture and injury zones are never exposed. The reduction is by indirect means and does not jeopardize the blood supply of the bony fragments in the zone of comminution. Locked intramedullary nailing also helped to establish clearly the biological and biomechanical differences between diaphyseal fractures and articular fractures. Diaphyseal bone requires only the reestablishment of length, rotation, and axial alignment for normal function. Locked intramedullary nailing showed conclusively that the displacement of intermediary fragments was not a significant factor, and that as long as the viability of these fragments was not interfered with, they rapidly incorporated in the abundant callus that would form. Articular fractures, in contrast, required anatomical reduction and absolutely stable fixation. Locked intramedullary nailing is only relatively stable. It is a form of splinting, an elastic form of fixation. Guided motion, the result of splinting, results in stimulating callus formation. It was also recognized that only living bone is capable of producing callus – thus the need to preserve the blood supply of the bony fragments. Closed locked intramedullary nailing results in rapid healing, low complication rate, and excellent return of full function. It is the best example of the benefits of minimally invasive surgery, of indirect reduction, of preservation of the blood supply of bone, and of splinting to induce the rapid formation of callus and union.

The desire to reproduce with plates the effects of closed intramedullary nailing resulted in the development of the techniques of indirect reduction which were coupled with bridge plating. In bridge plating the plate spans the zone of injury and fragmentation of bone. No effort is made to reduce the intervening fragments. Once length, rotation, and axial alignment are achieved the plate is fixed to the main fragments. The plate acts as a splint and provides relative stability, which stimulates callus formation.

When a force is applied to an extremity to produce a fracture, it creates a zone of injury. The zone of injury encompasses the bone and its soft tissue envelope. The severity of the injury to the soft tissue envelope is a reflection of the amount of energy involved in producing the fracture. Surgical exposure of the fracture through the zone of injury is not infrequently complicated by problems with wound healing, which may result in sepsis. The desire to gain access to the bone as one does in closed intramedullary nailing without having to cut through the injured soft tissues resulted in the development of the technique of minimally invasive plate osteosynthesis (MIPO). MIPO consists of precontouring the plate to the shape of the bone. An small incision is then made at a point removed from the fracture, which allows the plate to be slid under the soft tissue envelope, under the muscle, and across the fracture zone. Once indirect reduction is carried out, the plate is fixed to the other main fragment of the bone.

Attempts to execute MIPO with conventional plates ran into many technical problems. This, coupled with the considerable research evidence which indicated that conventional plates even if slid under the muscle envelope without direct interference with the zone of injury and fragmentation still interfered with the blood supply of bone because of the manner in which these plates were fixed to bone, stimulated further development in plate design and the manner of their fixation to bone. This resulted in the evolution of an entirely new generation of implants and manner of fixation referred to as the LISS plate (see Chap. 17, "Supracondylar Fractures of the Femur"). These locked plates or internal fixators are designed to be slid under the soft tissue envelope through minimal exposures. Reduction of the fracture follows by indirect means, and the plates are then fixed to the underlying bone by means of "locked screws" which make it possible for the plate to provide fixation without making contact with the underlying bone. Thus MIPO is capable of mimicking all the advantages of locked intramedullary nailing, that is, minimal exposure, closed surgical technique, indirect reduction, splinting of the fracture, with rapid callus formation and healing for bone segments not suitable for intramedullary nailing. The LISS and the locked compression plates are examples of these newly developed systems of bone stabilization designed to optimize MIPO and secure all its advantages when treating fractures.

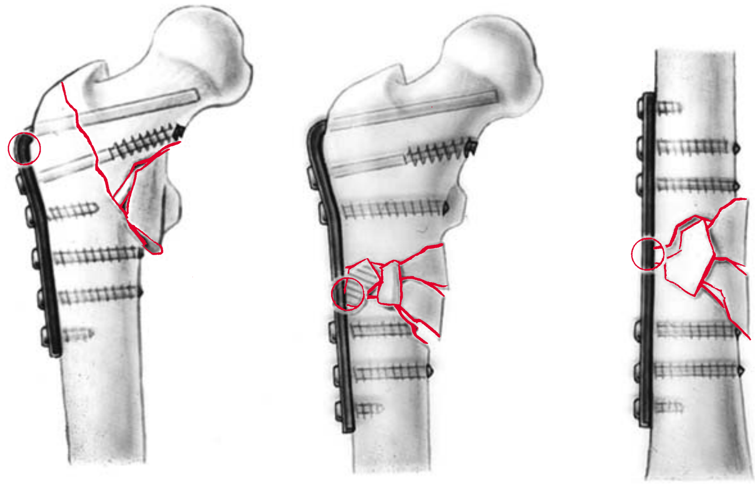


Fig. 1.23. Examples of deficiencies of the cortex opposite the plate which will result in cyclic bending of the plate and in its ultimate failure. (From Müller et al. 1979)

1.9 Implant Failure and Bone Grafting

Metal plates or other devices, no matter how rigid or how thick and strong, will undergo fatigue failure and break if subjected to cyclical loading. Metal is best able to withstand tension; bone is best able to withstand compression. Thus, in an ideal internal fixation, the biomechanical arrangement should be such that the bone is loaded in compression and the metal in tension. If a defect is present in the cortex opposite the plate, and the bone is under bending load, the fulcrum will move closer and closer to the plate until it eventually falls within the plate (Fig. 1.23). Consequently, with repetitive loading, even if due only to muscular contraction, the implant is repeatedly cycled and may fail. Internal fixation can therefore be viewed as a race between bone healing and implant failure.

In order to prevent the possibility of implant failure after stable fixation, whenever there is comminution, whenever there is a defect in the cortex opposite the plate, whenever there is devitalization of fragments (as is frequently the case in high-velocity injuries), and whenever enormous forces must be overcome (as in plating of femoral shaft fractures), the fracture should be bone-grafted. Such a graft, once it becomes incorporated into an osteoid bridge opposite the plate, rapidly hypertrophies and matures because it is subjected to compressive stresses. As soon as it reestablishes the continuity of bone opposite the plate, it acts as a second plate and prevents the cycling and inevitable fatigue failure of the implant (Fig. 1.24).

In stable fixation of a multifragmentary fracture, union depends on the revascularization of the dead fragments. As a result, union is slow and failure to bone-graft is the most common cause of failure of stable internal fixation. In bridge plating, union is rapid and by callus. As a result, the techniques of indirect reduction and bridge plating have made bone grafting of diaphyseal and metaphyseal multifragmentary fractures unnecessary. Bone grafting is now largely reserved for metaphyseal defects of articular fractures and for open fractures.

The newly developed LCPs, in which the anchoring screws have angular stability because they are fixed to the plate and which function biomechanically like an internally placed external fixator pro-

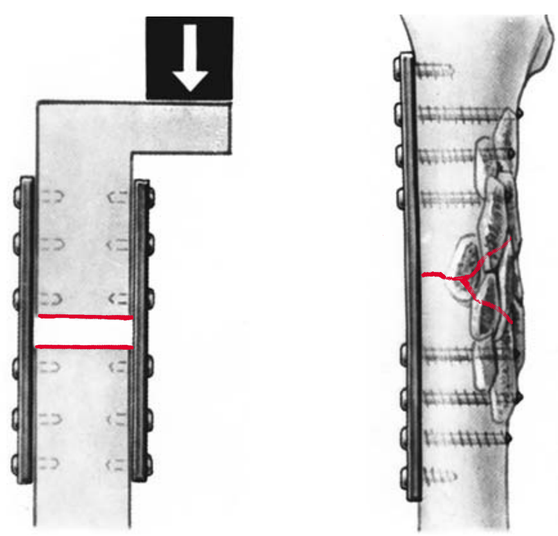


Fig. 1.24. Once it becomes incorporated into an osteoid bridge, a bone graft, if it is under compression, rapidly matures and hypertrophies. It reestablishes the continuity of the bone opposite the plate and prevents further cycling of the plate and its failure. (From Müller et al. 1979)

viding relatively stable elastic fixation, can be used on simple fractures as well as multifragmentary fractures. Their very secure anchorage to the bone (the result of angular stability of the screws) allows the fixation construct with an LCP to be more elastic than a conventional plate fixed to bone, which has made it possible to fix simple fractures with this implant without supplementing the plating with a bone graft. The elasticity that is distributed over the whole construct prevents stress concentration at the fracture. This makes it possible for callus to arise and for secure union, without the risk of implant failure and non-union.

Following removal of an implant, the bone must be protected from overload. The screw holes act as stress raisers, and if the bone is suddenly loaded before the screw holes have filled in – a process that takes 6–8 weeks in experimental animals – the bone may fail. Similarly, the ridges that frequently develop on each side of the plate should not be osteotomized, as this further weakens the bone and may contribute to its failure.

Implant removal is carried out only if there are specific indications. It is a procedure with inherent risks and should not be entertained lightly.

1.10 Implant Removal

Early on after fracture, bone that has united by primary bone healing is weaker than that united by callus. A callus, because of its spatial disposition, is further away from the central axis of bone than a plate, and therefore is in a mechanically more advantageous position to withstand force. The osteons of primary healing are closer to the central axis, and the union is therefore mechanically weaker.

Primary bone healing is also weaker than that by callus, because it undergoes a tremendous remodeling, which is manifested by a proliferation of haversian canals. Thus, such bone, although unchanged in its cross-sectional diameter, contains less bone per cross-sectional area because of the haversian proliferation. This continues until the accelerated remodeling ceases and the architecture gradually returns to normal. Based on their studies, Matter et al. (1974) suggested that the intense remodeling subsides some 12 months or so after fracture. Factors which prolong the remodeling phase are the patient's age, the degree of comminution, the degree of devitalization, the size of the gaps, the accuracy of the reduction, the stability of the fixation, and whether the fracture was bone-grafted. Furthermore, it is important to note whether there were any signs of instability during the time of healing or whether the fracture progressed uneventfully to union.

All these factors must be borne in mind when implant removal is being contemplated. If the implant is removed prematurely, the bone will fail and refracture. We feel that most implants should be left in place for 2 years before their removal is contemplated. This timing may be modified by the factors indicated in the preceding paragraph.

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