AOTRAUMA

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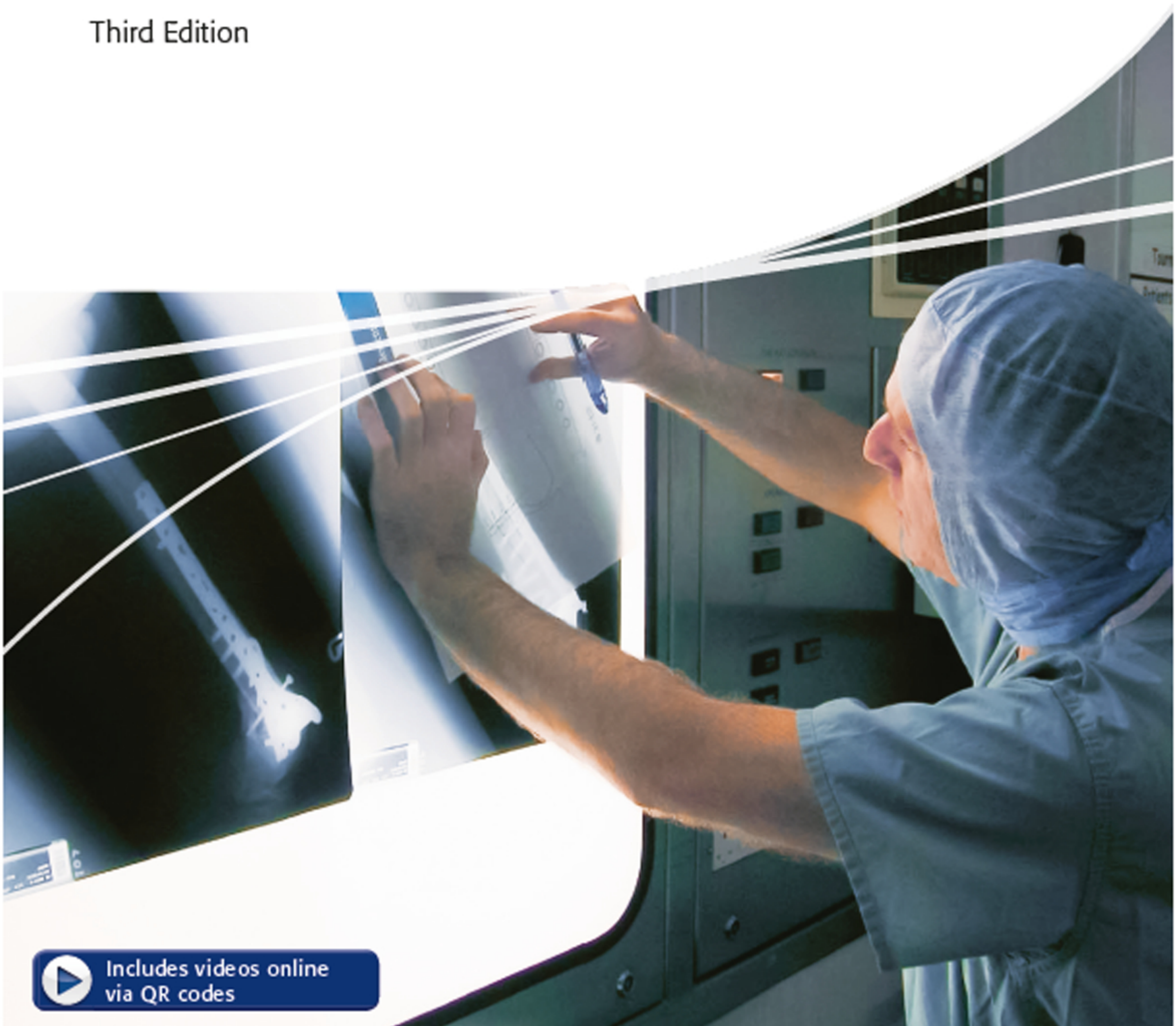
AO Principles of Fracture Management

Third Edition



Includes videos online via QR codes

Section 3
Reduction, approaches, and fixation techniques

Reduction and approaches

Techniques of absolute stability

Techniques of relative stability

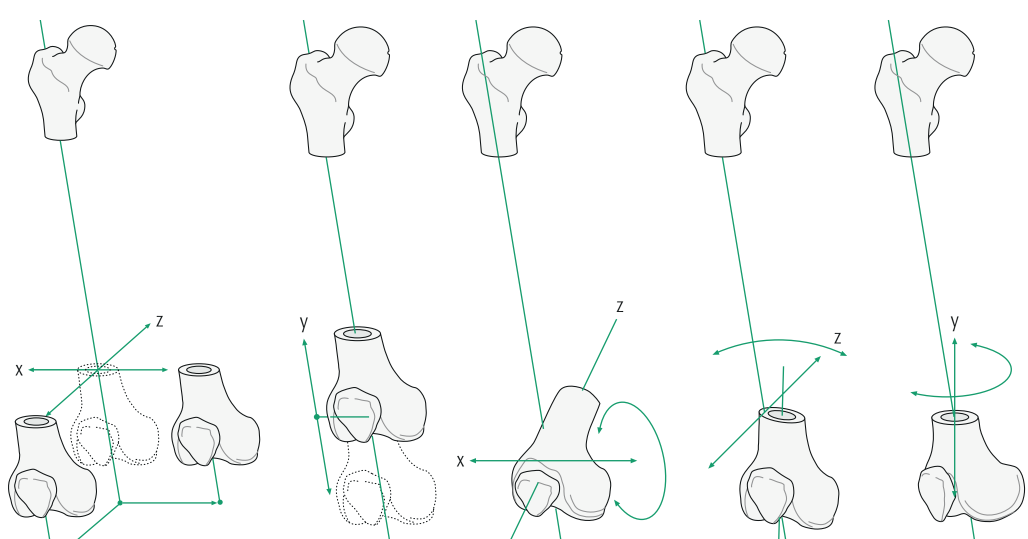
3.1.1 Surgical reduction

Rodrigo Pesantez

1 Displacement of fragments, deformation, and impaction of bone

A diaphyseal fracture usually separates the bone into two main fragments—proximal and distal—with their adjacent joints. There are six basic ways in which these main fragments can displace in relation to each other: three pairs of translational displacements, and three rotations along and around the x-, y-, and z-axes. Most fractures displace in a combination of ways. The degree and direction of displacement of the fracture fragments reflect the vectors of external forces and the pull of the muscles that remained attached (**Fig 3.1.1-1**). In children, plastic deformation can occur in diaphyseal bone without complete discontinuity of the bone cortex.

Displacement in diaphyseal and metaphyseal bone can readily be detected with conventional x-rays taken in two planes perpendicular to each other. In the metaphysis and epiphysis, 45° oblique views may be helpful but computed tomography with multiplanar reconstruction is often needed to fully assess fragmentation, displacement, deformation, and impaction. Careful analysis of the site and extent of bone deformation as well as the direction and degree of displacement is important to identify the best reduction technique which in turn will help select the most appropriate surgical approach, fixation technique, and choice of implant.



a b c d e

Fig 3.1.1-1a–e Translational and rotational displacement.

a–b Translational or linear displacement can occur along all the three axes in space; the x-, y-, and z-axis. Displacements along the x-axis are medial or lateral and those along the z-axis are anterior or posterior (**a**). Those along the y-axis are shortening or lengthening (**b**).

c–e Rotational displacement is also possible around the three axes in space. Angular displacement in the sagittal plane (around the x-axis) is an axial malalignment in flexion or extension (**c**), in the coronal plane (around the z-axis) an axial malalignment in abduction or adduction (**d**), and in the transverse plane (around the y-axis) a rotational malalignment (**e**).

2 Fracture reduction

Reduction is the act of restoring the correct relation and position of fracture fragments. This includes the process of reconstruction of impacted cancellous bone and articular fragments. In other words, reduction is the recreation of the spacial relationship of one fragment to another (**Video 3.1.1-1**).

Reduction reverses the process which created fracture displacement during the injury and calls for forces in opposite directions to those which produced the fracture (**Fig 3.1.1-2**). Analysis of the displacement and deformation, together with knowledge of the site of muscle insertion and muscle pull, helps to plan the tactical steps needed to achieve reduction, independent of the treatment method (ie, operative or non-operative) [1–3].

Video 3.1.1-1 Direct and indirect reduction.

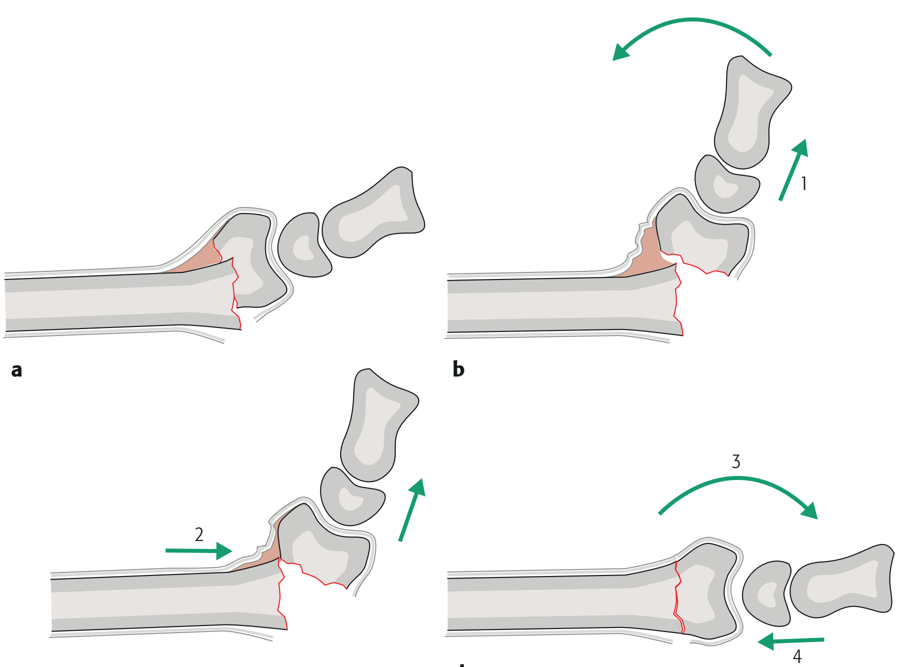


Fig 3.1.1-2a–d Closed reduction with reversing of the forces that have created the fracture displacement.
- **a** Distal radial fracture with shortening, posterior displacement, and dorsal angulation. The intact periosteum on the dorsal side may act as an obstruction to reduction by traction because the fragments are interlocked.
- **b** The first step to reduce this fracture consists in disengaging the bone ends by extension of the wrist and dorsally angulated traction to relax the soft-tissue hinge (arrow 1).
- **c** Under dorsal traction the distal fragment is pushed (arrow 2) into its correct position, with the dorsal fragment ends reduced into contact.
- **d** Adding a flexion force and continuing the push (arrow 3), the distal fragment will realign and the fragments are interlocked (arrow 4).

2.1 Aim of reduction

In the diaphysis and metaphysis, the aim of fracture reduction is to restore length, alignment, and rotation so that the joints above and below the fracture are in the correct position.

This is regardless of whether the fracture is simple or multifragmentary, segmental, or has bone loss. Every fragment does not have to be perfectly reduced but the bone must be restored to its original length, alignment, and rotation (**Fig 3.1.1-3**).

In articular fractures, the aim of reduction is perfect restoration of the joint surface to provide a congruent and stable joint with normal movement. In some cases there may be irreparable damage to the cartilage due to impaction at the time of injury. Anatomical reduction of the joint surface, as well as restoring axial alignment, especially in the lower extremity are factors that the surgeon controls to reduce the risk of posttraumatic osteoarthritis [4]. Ideally, no residual displacement should be accepted. However, different joints with different loading conditions seem to have different tolerance [4]. A concentric joint, such as the hip or ankle, depends much more on perfect articular congruity [5, 6] than a nonconcentric joint, such as the knee joint. In the knee, the restoration of the axial alignment of the whole limb and the restoration of ligament and meniscal stability may be as important as anatomical reconstruction of the articular surface.

To achieve a perfect reduction the surgeon must understand the displacement of the fracture fragments and plan reduction maneuvers in advance. Reduction and maintenance of reduction is often the most difficult part of surgery and master surgeons plan their reductions and anticipate problems.

2.2 Reduction techniques

Reduction techniques must be gentle and create as little additional damage as possible.

Reduction techniques must preserve the vascularity of the soft-tissue envelope and any remaining tissue attachments to bone fragments. Bone healing will be delayed or come to a stop if the biological environment is critically disturbed. The risk of infection is also increased [7–9].

The degree of stability achieved by fixation (absolute or relative stability) is the mechanical input for the biological response and determines the healing pattern (primary bone healing or callus formation).

The healing process is modulated by any additional damage to the bone and the surrounding soft-tissue envelope caused by the surgical exposure, reduction maneuvers, and the application of fixation devices.

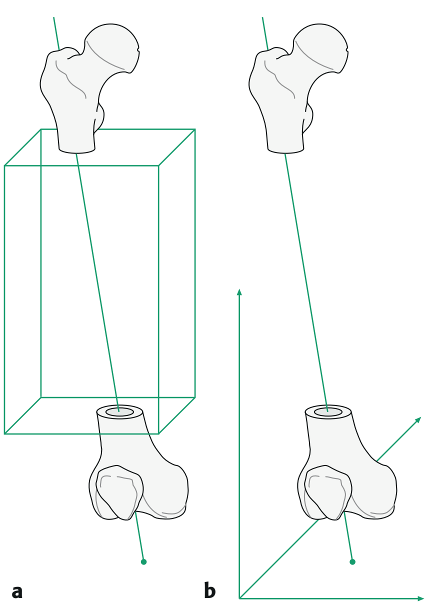


Fig 3.1.1-3a–b Fracture reduction in the diaphysis.
The fracture zone is like a black box, whose content is of no or only minor importance with regard to the primary aim of reduction. After reduction, the proximal and the distal main fragments should be relocated into their correct positions in space.

There are two fundamental techniques for fracture reduction: direct and indirect reduction (**Table 3.1.1-1**).

Direct reduction means that hands or instruments are in contact with fracture fragments for manipulation under vision.

In simple diaphyseal fractures (eg, simple forearm shaft fractures), direct reduction is technically straightforward and the results are reproducible. Exact coaptation of the two main fragments restores anatomical length, alignment, and rotation. A careful surgical exposure should not add vascular damage to the bone or soft tissues and should maintain biology. However, this is only true if surgery is done gently, with meticulous soft-tissue handling, and limited periosteal exposure of the bone [10].

In more complex diaphyseal fractures, direct reduction techniques may result in attempts to expose, reduce, and stabilize every single fragment. In doing so, the surgeon may devascularize these fragments by stripping the periosteum and soft tissues.

The repeated use of bone forceps and other reduction tools may completely devitalize the fragments. X-rays do not show how much manipulation occurs during surgery. This can have disastrous consequences for the healing process, including delayed union, nonunion, infection, and implant failure. Only by understanding and respecting the biology of bone, periosteum, and soft tissues can the surgeon avoid failure after open reduction and internal fixation [1, 9].

	Direct reduction	Indirect reduction
Main field of application	Articular fractures and simple diaphyseal fractures	Specific articular fractures (ligamentotaxis), multi-fragmentary diaphyseal fractures (soft-tissue taxis)
Difficulty to achieve reduction	Relatively easy	Demanding
Control of reduction	Direct exposure, x-rays, image intensifier	Technical: clinical, radiological, or image intensification, arthroscopy, computer assisted
Soft-tissue dissection	Relatively extensive	Limited
Bone devascularization	Relatively extensive	Minimal
Usually employed fixation principle	Absolute stability	Relative stability

Table 3.1.1-1 Comparison of two reduction methods: direct and indirect.

Indirect reduction means that fragments are not exposed and are manipulated by applying corrective force at a distance from the fracture. Radiological imaging is required to ensure appropriate positioning of the fracture.

Correct reduction by indirect techniques may be difficult to achieve. It requires understanding of the fracture pattern, anatomy (muscle pull), and meticulous preoperative planning. The actual process of reduction is often more demanding and necessitates the use of an image intensifier. In biological terms, indirect reduction techniques offer significant advantages. If correctly applied, they add minimal surgical damage to tissues. All reduction tools are applied away from the fracture focus so that any local damage from the instruments themselves will not affect fracture healing.

Most instruments and implants available today can be used as tools for either direct or indirect reduction. The success in preserving the biology of the tissues is not dependent on any specific instrument or implant but rather on the skill of the surgeon. It cannot be emphasized enough how important planning is to this process:

Converting an intended indirect reduction to an unplanned open, direct reduction may result in significant soft-tissue damage. This may not be visible on x-rays or recorded in the operation record but puts the patient at additional risk of serious complications.

2.2.1 Traction or distraction

The most important mechanism to reduce a fracture is traction. This is normally applied in the long axis of the limb.

In comminuted articular fractures, traction across a joint may reduce fragments by ligamentotaxis. Traction may be applied manually, by means of a fracture table, or by applying a distractor (**Video 3.1.1-2**). The fracture table requires that traction is applied across at least one joint. The disadvantage is that the limb cannot be moved by the surgeon and the surgical approach or limb alignment may be compromised. The distractor, applied directly to the main fragments, permits maneuvering of the limb during surgery. However, its application is demanding and requires tension; angular or rotational corrections are difficult and the construction may be cumbersome. There is also an inherent tendency for curved bones to straighten during distraction and so the eccentric force produced by the unilateral distractor may produce additional deformity (**Fig 3.1.1-4**).

The distractor can also be applied across joints to aid with the reduction of articular injuries through ligamentotaxis. This also helps direct visualization of the joint surface by distracting the joint (**Fig 3.1.1-5**).

The external fixator can be used for indirect reduction but gentle lengthening is more difficult than with the distractor. By applying traction across a joint, ligaments, and soft tissues around the fracture area can help to achieve reduction, either by ligamentotaxis or soft-tissue reduction. The main fields of application are comminuted metaphyseal/articular segments when the soft-tissue condition or fracture fragmentation does not permit open reduction and stabilization techniques [10].

The use of traction and distraction to reduce fractures is also used in pelvic and acetabular surgery with specially designed frames and percutaneous clamps.

2.2.2 Instruments for reduction

Various reduction forceps are shown in **Table 3.1.1-2**.

Video 3.1.1-2 The large distractor can be used for indirect reduction of a femoral fracture.

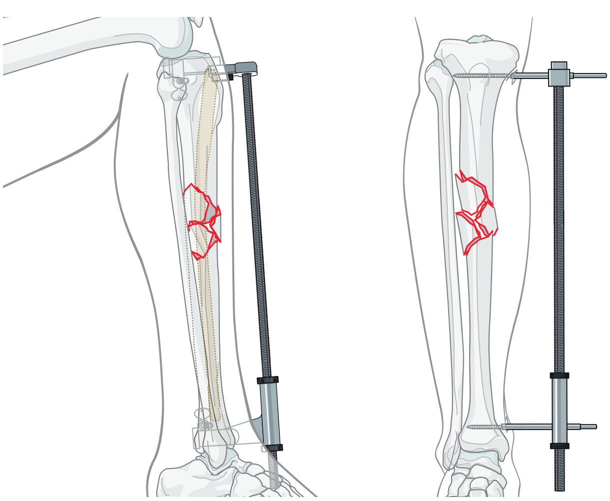


Fig 3.1.1-4 Unilateral distractor used for indirect reduction of multifragmentary tibial shaft fractures. Note the posterior position of the Schanz pins to allow introduction of an intramedullary nail.

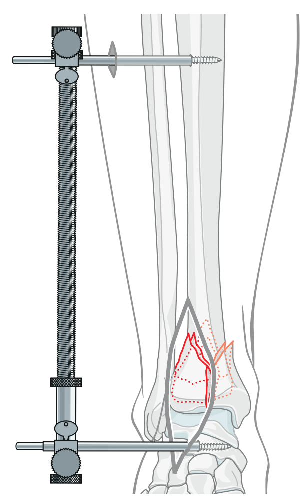


Fig 3.1.1-5 Distractor applied across the ankle joint to allow treatment of a pilon fracture. The distractor provides indirect reduction or alignment and rotation plus access to the joint to allow direct reduction of articular fragments.

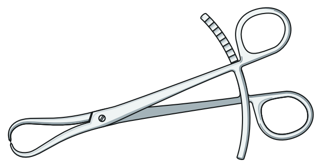
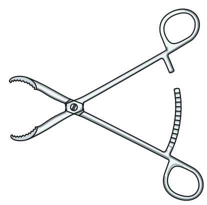
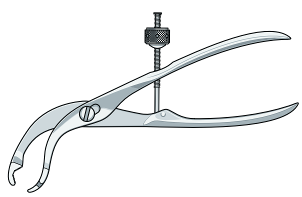
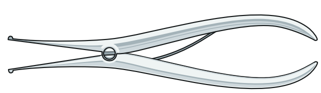
Instrument	Image of instrument	Description	Application technique
Reduction forceps with points (Weber forceps)		This instrument has points on each prong so they can hold into the bone and help to manipulate and reduce fragments. Very helpful in most type A and some type B1 and B2 fractures.	Put each tine of the forceps on the bone (directly or through a small drill hole) and manipulate the fracture fragments until reduction is achieved (**Videos 3.1.1-3–4**).
Reduction forceps, toothed		This instrument is similar to the pointed reduction clamps but its tine ends are more aggressive on the bone, it can help in plate application (holding plate) on small bones (forearm and fibula).	Apply one tine end to the bone and the other tine to the plate so it can hold the plate while fixing it with screws (**Fig 3.1.1-8**). It can also be used to manipulate bone fragments in simple fracture patterns using the one or two forceps technique.
Bone holding forceps, self-centering (Verbrugge forceps)		One end is similar to a Hohmann retractor and the other one is designed to hold the plate to the bone. It goes around the bone and is less soft-tissue friendly.	The Hohmann retractor end goes round the bone and the plate holding end will hold and center the plate to the bone (**Fig 3.1.1-9**). It can also provide compression if used in the pull technique (**Fig 3.1.1-8b**).
Bone spreader		It helps to achieve distraction of fragments and gain length using the push-pull technique.	Its ends are supported by an independent screw in the bone and the plate end on the other side to achieve distraction (**Fig 3.1.1-8a**, **Video 3.1.1-12**).

Table 3.1.1-2 Design and function of reduction forceps.

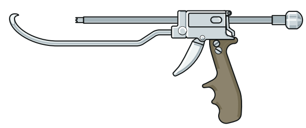
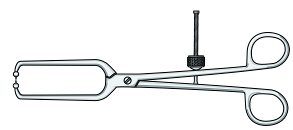
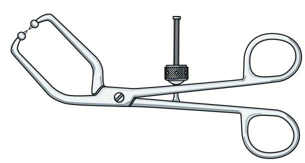
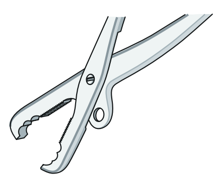
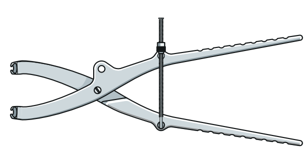
Instrument	Image of instrument	Description	Application technique
Colinear reduction forceps		It is designed to provide linear force and reduce/compress fracture fragments or to hold the plate to the bone. It has different arms that can be attached to it according to the desired fusion and bone size.	It can be applied percutaneously to compress (distal femoral fractures, syndesmosis) or open reduction (posterior column acetabular fractures through anterior approach). It also helps to hold plate position in MIPO techniques.
Pelvic reduction forceps with ball points (Queen tong)		This forceps is similar to a Weber forceps but it is bigger and provides higher force. The balls prevent overpenetration of the cortex.	In articular injuries, distal femur and proximal tibia it can help to reduce simple fracture patterns and compress them through the stab incisions (**Fig 3.1.1-11**).
Angled pelvic reduction forceps (Matta forceps)		The angulation of this forceps allows them to reach difficult areas in pelvic and acetabular surgery.	It can help to compress and reduce transverse fracture patterns in acetabular fracture surgery through the posterior approach (sliding it through the greater sciatic notch).
Pelvic reduction forceps (Farabeuf forceps)		This forceps has two arms with ends designed to grasp screw heads (3.5 and 4.5 mm).	Once independent screws are attached to each fracture end the forceps can grasp each screw head and manipulate the fragments in different planes (**Video 3.1.1-6**). It can also be used to grasp anterior column fracture fragments in the anterior approach.
Pelvic reduction forceps (Jungbluth forceps)		This forceps has two arms with ends designed to be fixed to bone through screws (3.5 and 4.5 mm).	Each arm of the forceps is fixed to the bone with a screw and then each arm is attached to the other to provide manipulation of fracture in different planes (**Fig 3.1.1-13**, **Video 3.1.1-6**).

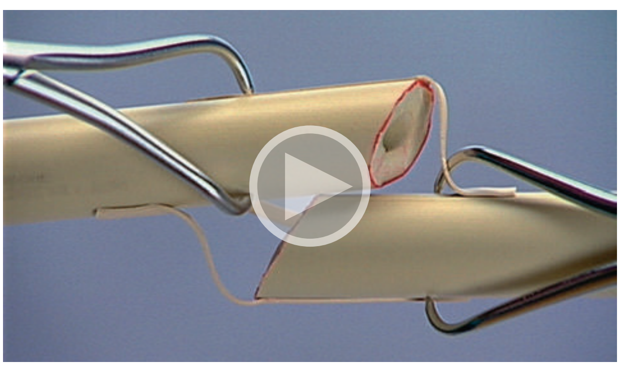
Table 3.1.1-2 (cont) Design and function of reduction forceps.
Abbreviation: MIPO, minimally invasive plate osteosynthesis.

Reduction forceps with points (Weber forceps)

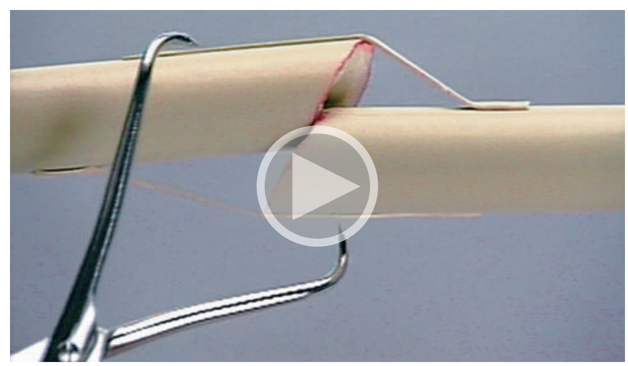
The pointed reduction forceps is the primary choice of reduction tool because it is gentle to the periosteal sleeve and can be used for direct and indirect reduction.

The two-forceps technique consists of seizing each of the two main fragments of a transverse fracture with a reduction forceps (**Video 3.1.1-3**). Reduction can be achieved by manual traction, and in a transverse fracture intrinsic stability then allows removal of the forceps without loss of reduction (**Fig 3.1.1-6**).

For an oblique fracture plane that needs some lengthening, the pointed reduction forceps engages on the main fragments on each side of the fracture with a slight tilt of the forceps (one-forceps technique). By combining compression with a rotational movement of the forceps, correction of length can be obtained (**Video 3.1.1-4**). To keep the fragments reduced, the first forceps often has to be replaced by a second one perpendicular to the fracture plane (**Fig 3.1.1-7**).



Video 3.1.1-3 The two-forceps technique of fracture reduction.



Video 3.1.1-4 The single-forceps technique for reduction of oblique fractures.

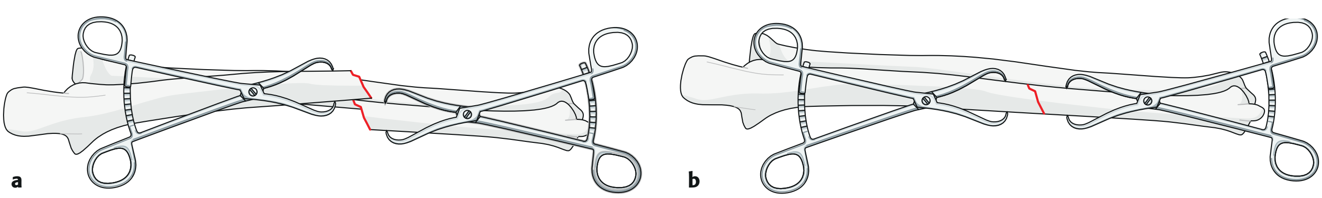


Fig 3.1.1-6a–b Direct manual reduction using two pointed reduction forceps.
a Each main fragment is held with a pointed reduction forceps.
b Lengthening is achieved by manual traction while correct rotation and axial alignment can be controlled with the forceps.

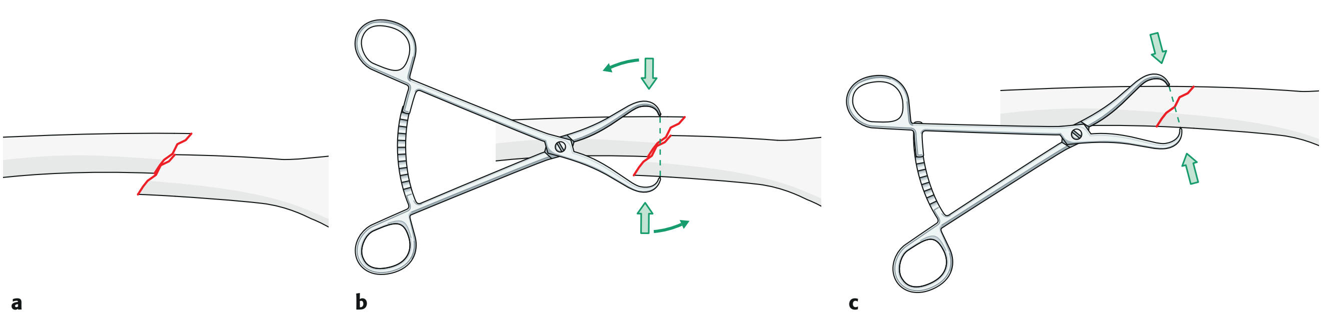


Fig 3.1.1-7a–c Direct reduction of an oblique diaphyseal fracture.
a Both fragments are held with the slightly tilted, pointed reduction forceps.
b By gently rotating and compressing the forceps the bone is lengthened and the fracture reduced.
c To secure reduction, a second forceps perpendicular to the fracture plane is applied.

Reduction forceps, toothed

This reduction forceps is a typical instrument used for direct fracture reduction.

Due to its dimension and the design of the jaws, the toothed reduction forceps has a tendency to slip on the bone surface, further damaging the periosteal envelope.

It is used to adjust and fine-tune fracture reduction and plate position.

Bone spreader

This device can be used for distraction if placed between two fragments or between the end of a plate and an independent screw 1 cm from the plate end (push technique) (**Fig 3.1.1-8a**).

Bone holding forceps, self-centering (Verbrugge forceps)

The main function of this forceps is to hold a plate to diaphyseal bone. Due to its design, it produces considerable circumferential exposure of the bone because its pointed end has to reach completely around the bone (**Fig 3.1.1-9**). A second function of this forceps is compression: the pointed end of the forceps may be hooked into an end hole of the plate while the broad end reaches around an independent screw head to pull the plate, thereby compressing the fragments (pull technique) (**Fig 3.1.1-8b**).

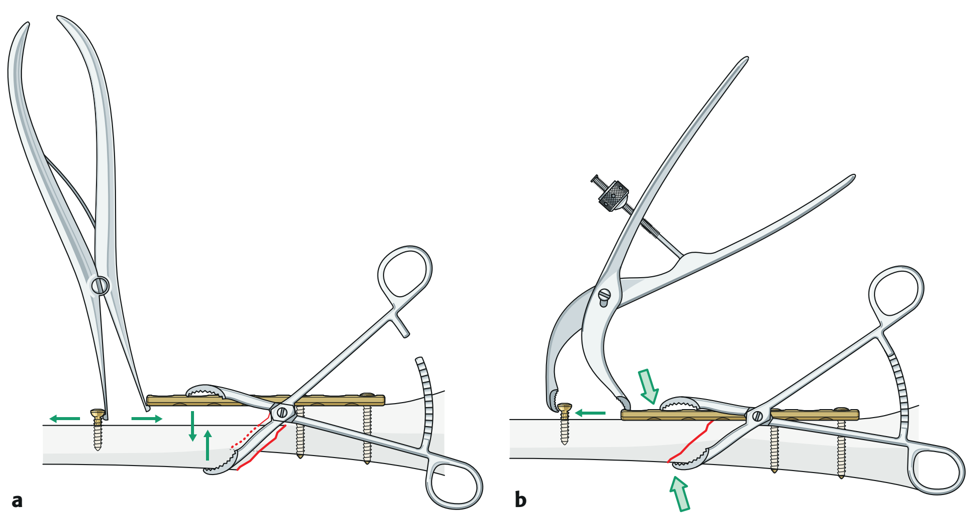


Fig 3.1.1-8a–b Push-pull technique.
a The bone spreader, placed between the end of a plate and an independent screw, can be used to distract or push apart the fracture for reduction.
b Using the same independent screw, interfragmentary compression can then be obtained by pulling the plate end toward the screw with a small Verbrugge forceps.

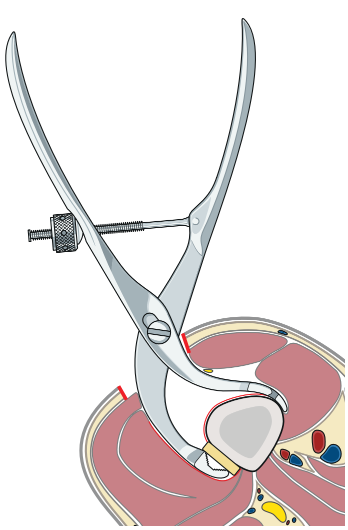


Fig 3.1.1-9 Verbrugge forceps are self-centering bone forceps that may be used to hold a plate. It should be used outside the fracture zone to minimize damage to the blood supply.

Colinear reduction forceps

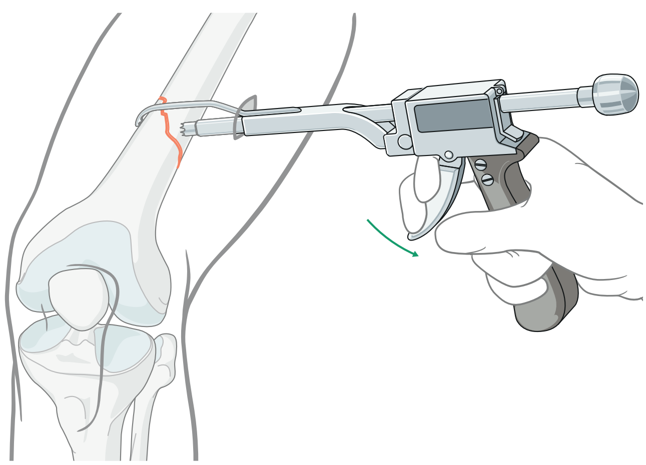
This forceps has a sliding mechanism that allows linear movement. The hook is designed to pass around the bone without stripping of soft tissues (**Fig 3.1.1-10**) [11].

Pelvic reduction forceps with ballpoints ("King tong clamp", "Queen tong clamp")

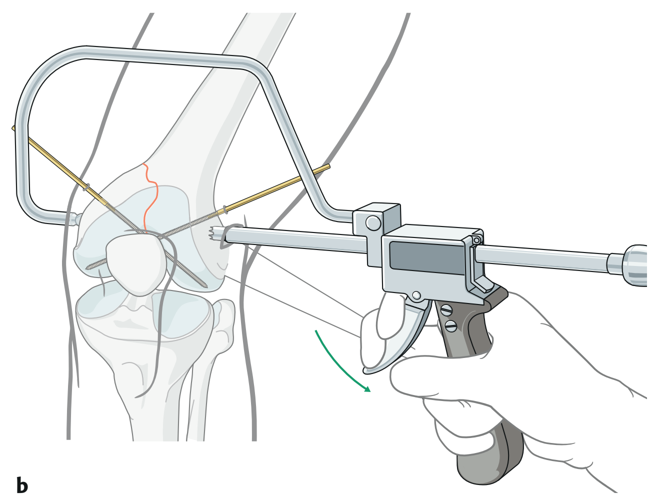
These reduction forceps are mainly used for reduction of pelvic, acetabular, and tibial plateau fractures. To avoid deep penetration of the points into bone, a mobile washer can be fixed to the ballpoints. The king tong forceps can also be used for indirect reduction of other articular fractures, such as the tibial plateau. One or both points of this forceps can be inserted percutaneously through stab incisions (**Fig 3.1.1-11**), while the wide arms of the forceps avoid crushing of soft tissues as the forceps are closed.

Angled pelvic reduction forceps (Matta forceps)

These reduction forceps are also used for pelvic and acetabular fractures. The angulation allows access to anatomical areas that are difficult to reach (eg, through the sciatic notch). The ballpoints and mountable washers reduce point forces on weak bone.



a



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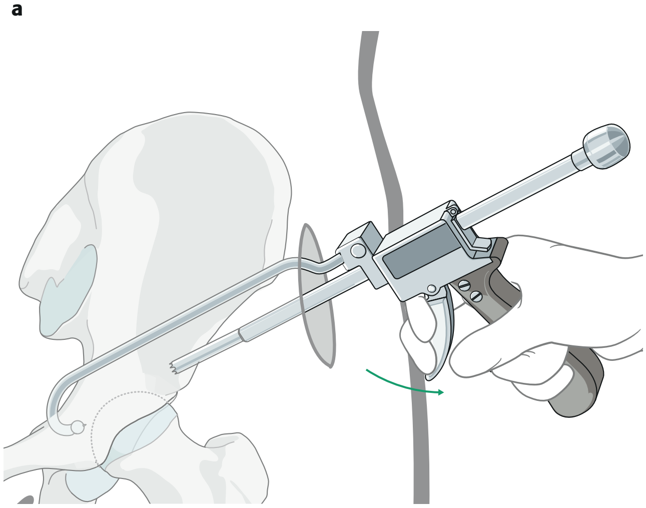


c

Fig 3.1.1-10 Colinear reduction forceps.
a Reduction of the femoral shaft using the Hohmann-style arm.
b Reduction of the femoral condyle using the periarticular arm.
c Reduction of the pelvis using the pelvic extension arm.

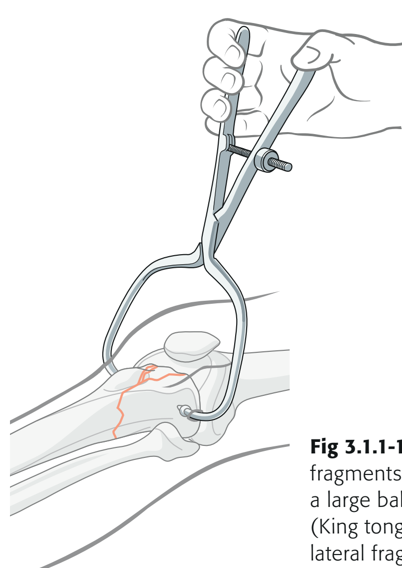


Fig 3.1.1-11 The position of large fragments can be manipulated with a large ballpoint reduction forceps (King tong) grasping the medial and lateral fragments through small stab incision.

Pelvic reduction forceps (Farabeuf forceps)

The Farabeuf forceps is designed to grasp screw heads inserted on either side of a fracture line (3.5 or 4.5 mm screws) (**Fig 3.1.1-12**). Manipulation of the forceps allows compression and also permits limited manipulations in two different planes (**Video 3.1.1-5**). However, distraction of the fracture gap is not possible.

Pelvic reduction forceps (Jungbluth forceps)

The Jungbluth forceps is fixed on both fragments with a 3.5 or 4.5 mm cortex screw. This allows the fragments to be moved and reduced in three planes (distraction and compression, as well as lateral displacement in two planes) (**Fig 3.1.1-13**, **Video 3.1.1-6**).

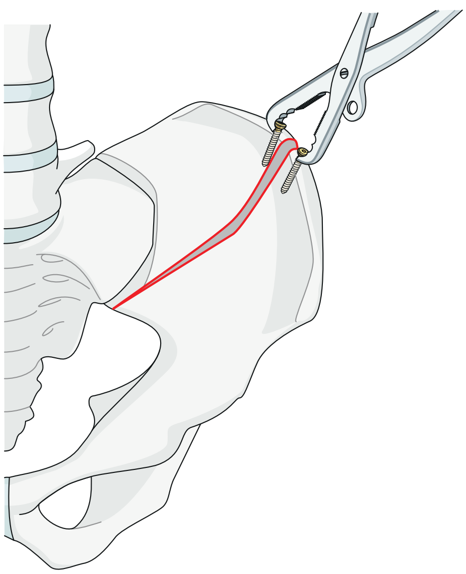


Fig 3.1.1-12 The Farabeuf forceps is mainly used for fracture reduction of the pelvic ring/iliac crest. It is anchored on both sides of the fracture with either 3.5 or 4.5 mm cortex screws. The forceps is helpful only to reduce a side-to-side displacement or to close a fracture gap. Distraction is not possible.

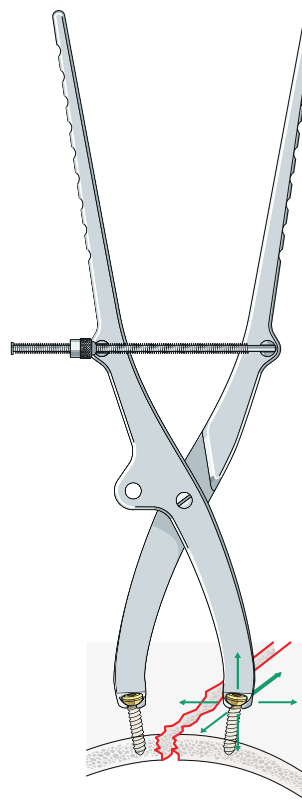
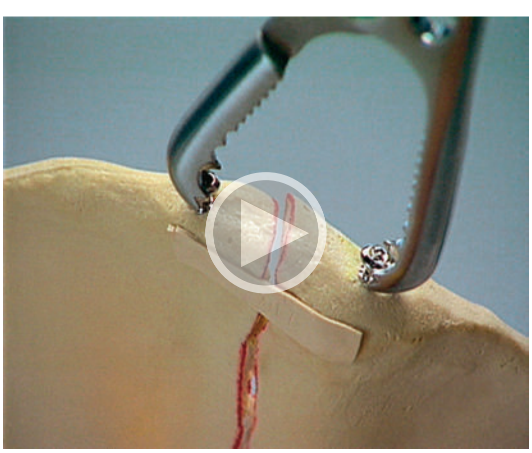


Fig 3.1.1-13 The Jungbluth forceps is fixed to fragments with 4.5 mm cortex screws. This firm connection allows translational reduction maneuvers in all three planes.



Video 3.1.1-5 Application of Farabeuf forceps using screw heads.

Video 3.1.1-6 Jungbluth forceps allow reduction in three planes.

Hohmann retractor

In cortical bone, the small tip of the Hohmann retractor can be used as a lever or pusher to achieve reduction. The tip of the Hohmann retractor is inserted between the cortices of two diaphyseal fragments. It is then turned around 180° to engage the cortex of the opposite fragment. With a bending force applied to the Hohmann retractor, the two cortices can be realigned, allowing gentle reduction of the fracture. Another turn of the retractor is usually needed to remove it (**Fig 3.1.1-14**) [1]. Because the tip of the retractor is entirely within the fracture, no additional soft-tissue stripping is created during this maneuver (**Video 3.1.1-7**). However, it may displace the fracture if there is an unrecognized crack or if the bone is osteoporotic.

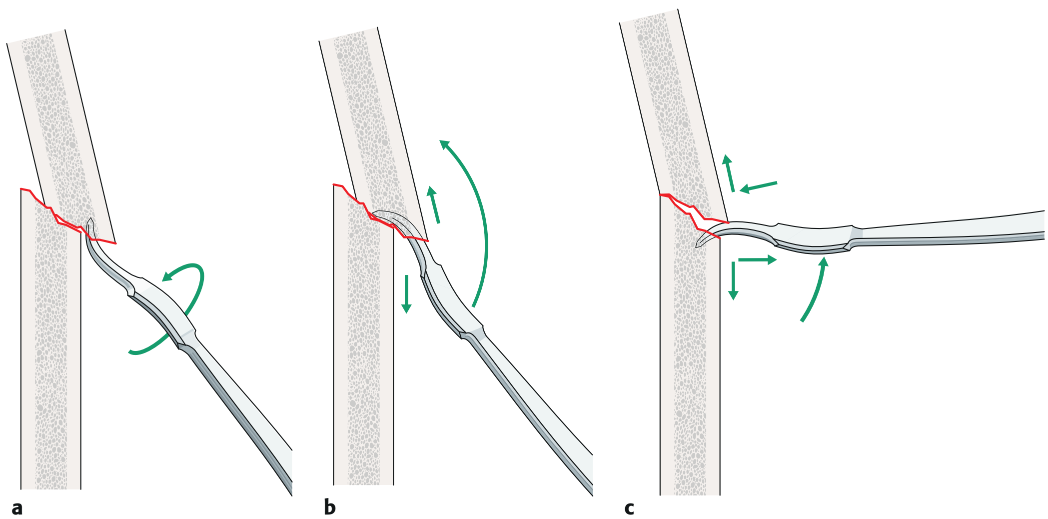
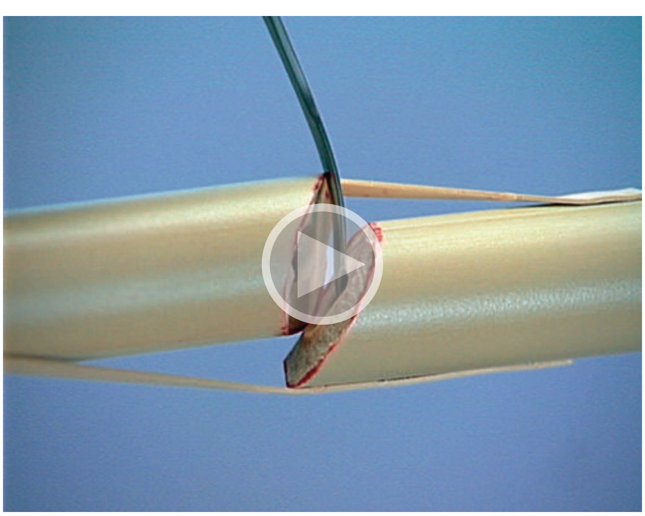


Fig 3.1.1-14a–c Diaphyseal reduction with the small Hohmann retractor.
In cortical bone, the tip of the Hohmann retractor is placed between the two fragments. By turning and bending the retractor handle the fragments can be disengaged and reduced. Another turn is usually required to remove the Hohmann retractor.

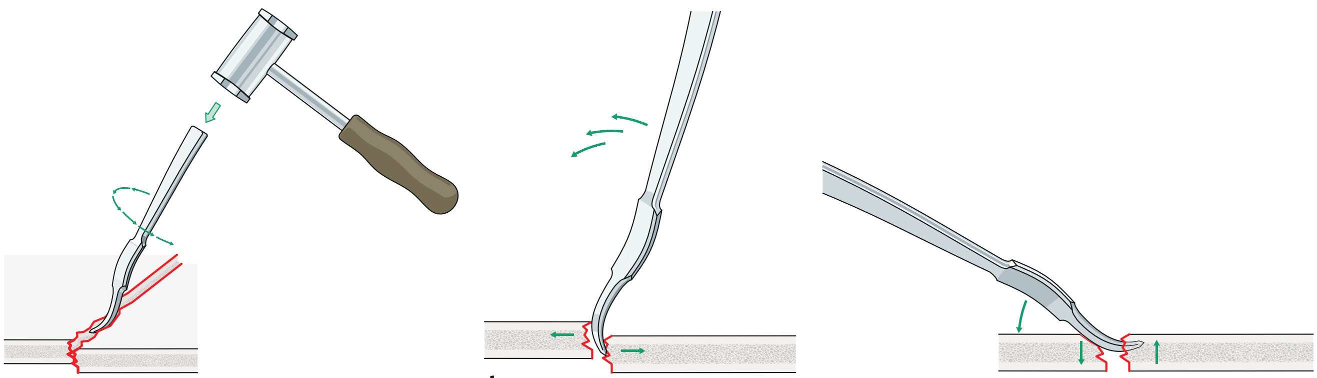


Video 3.1.1-7 Fracture reduction with a small Hohmann retractor.

A further application of the Hohmann retractor is to reduce a translational displacement in the cancellous bone of an iliac wing fracture. First the tip of the Hohmann retractor is lightly hammered into the bone. Then it is turned and reduction can be achieved with a bending force (**Fig 3.1.1-15**, **Video 3.1.1-8**). This maneuver usually produces a small zone of impaction on the thin cortex of the fragment pushed down.

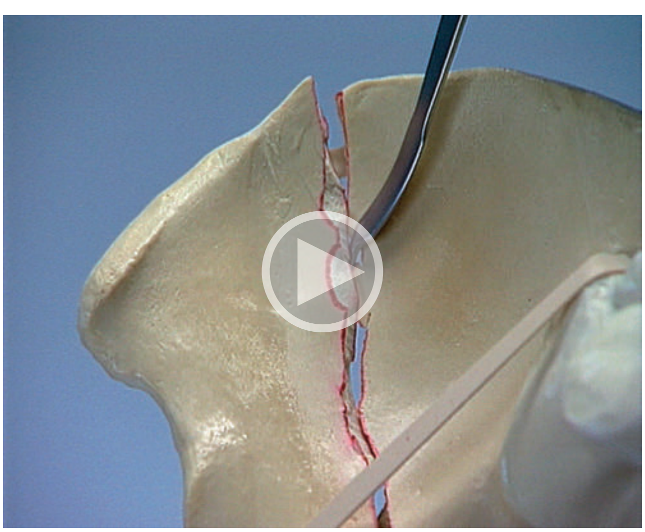
Ball spike, bone impactor, bone hook

Fracture reduction in one direction can be carried out by instruments designed to push or pull. Using the ball spike, fragments can be pushed firmly into the right position. The bone impactor, used from within, serves to disengage (elevate) impacted fragments from an articular surface. The hook (dental pick) or the regular bone hook can be most useful for fine tuning the reduction of a fragment.



a b c

Fig 3.1.1-15a–c Hohmann retractor for reduction in cancellous bone. By placing the slightly curved tip of a Hohmann retractor between two overlapping fragments and then turning and tilting the retractor the fracture may be reduced and brought to interdigitate. A precondition is a solid layer of bone.



Video 3.1.1-8 Reduction of iliac wing fracture with small Hohmann retractor.

Joystick reduction

This technique can be used with Schanz screws or K-wires to manipulate fracture fragments in different planes; it can be used alone or associated to other reduction techniques (distractors, reduction forceps). The insertion of a Schanz screw into the ischium is a common technique to manipulate the posterior column of the acetabulum (in case of a posterior column, transverse, or T-shaped fracture). The same technique may be used to control rotation of the femoral diaphysis or femoral condyle when reducing a supracondylar-intercondylar fracture. The open or percutaneous insertion of threaded or unthreaded K-wires allows manipulation of bone fragments with or without a direct view (**Fig 3.1.1-16**, **Video 3.1.1-9**) [3, 12].

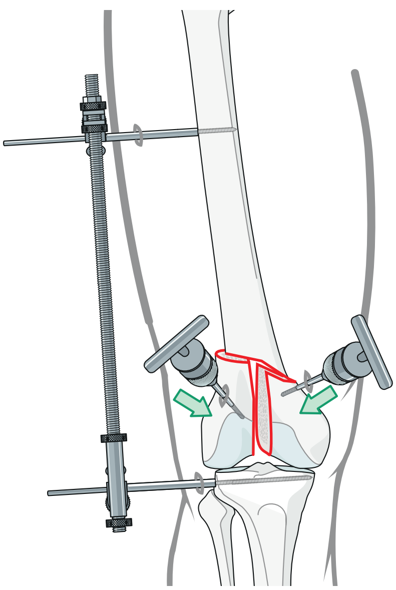


Fig 3.1.1-16 Joystick technique combined with femoral distractor.

Kapandji reduction

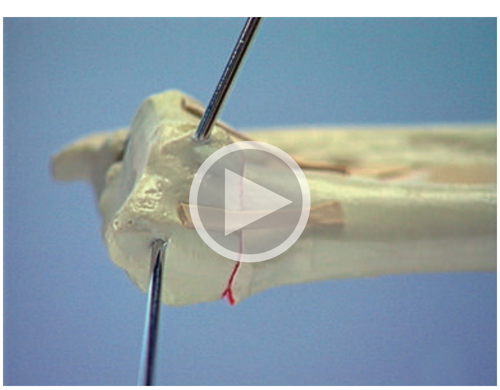
With a K-wire inserted through the fracture gap, the radiostyloid fragment of a distal radial fracture can be manipulated and rotated similarly to the technique with the Hohmann retractor. Definitive stabilization is achieved by completing the insertion of the K-wire into the opposite cortex of the bone (see chapter 6.3.3).

Cerclage wires

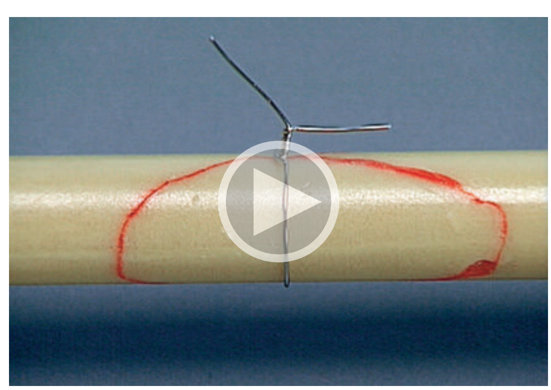
Cerclage is defined as circumferential, periosteal wire loops placed perpendicularly to the long axis of the bone. It exerts a centripetal force reducing and keeping radially displaced fragments together [13-16]. It can be used as a reduction tool and as fixation device. Nowadays the use of percutaneous application of cerclage wires using the minimally invasive technique and wire passer has been proved to do minimal harm to soft tissues and bone (**Fig 3.1.1-17**) [16]. Wähnert et al [15] have demonstrated that the stability provided by the cerclage wire is determined by the plastic deformation of the knurled twist, and the key is the innermost turn. This is achieved by applying at the same time torque and traction trying to pull the twist away from the bone (**Video 3.1.1-10**).

When applying cerclage as a reduction tool it should be applied at least 1 cm from the tip of the fracture, especially in oblique, spiral, and butterfly fragments. In large oblique or butterfly fragments several cerclage wires can be used.

Cerclage use has increased in recent years especially in periprosthetic fractures and spiral proximal or distal femoral fractures [13].



Video 3.1.1-9 Joystick reduction using K-wires in a distal radial fracture.



Video 3.1.1-10 Reduction with a cerclage wire. Soft-tissue stripping must be minimal.

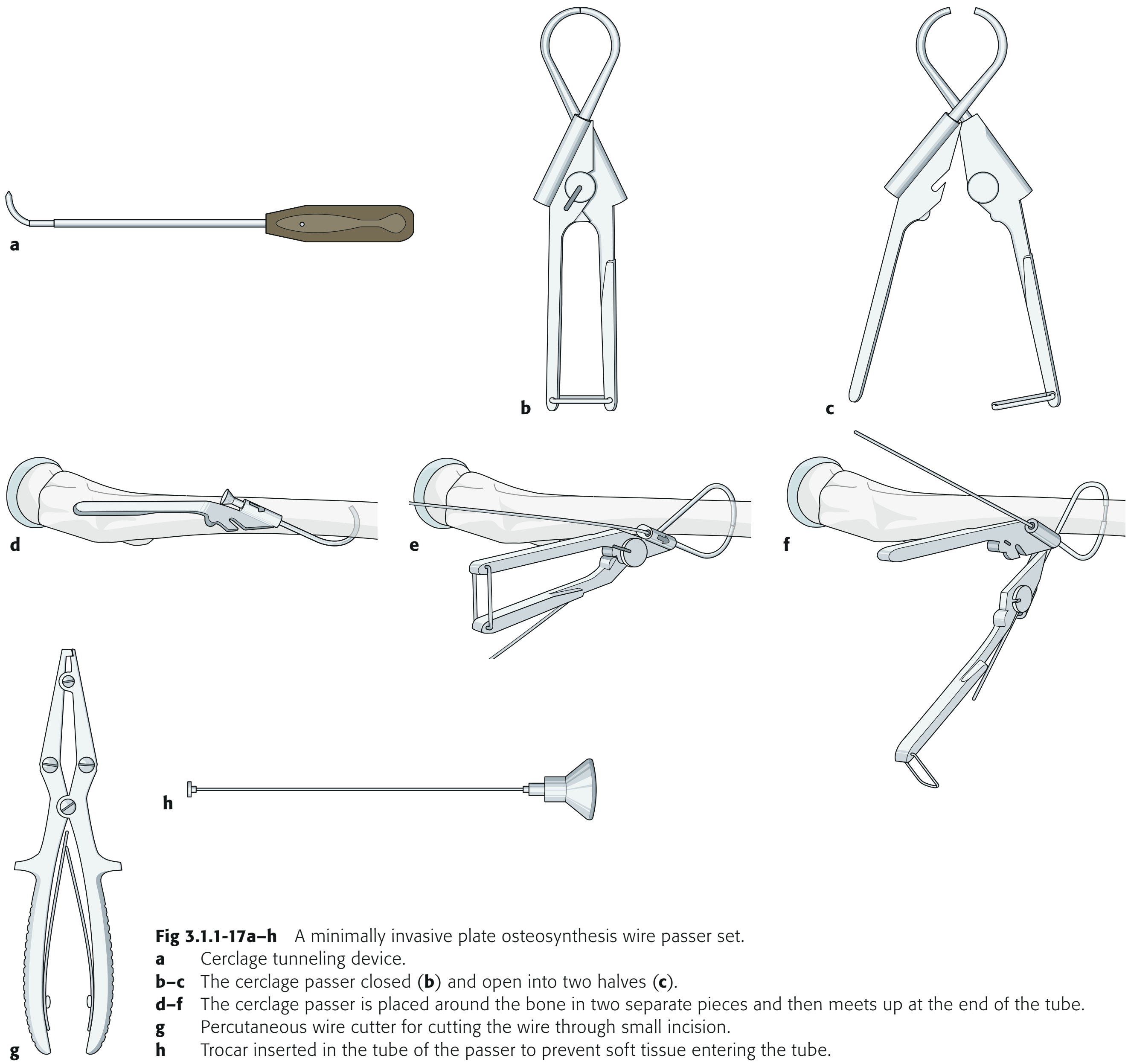


Fig 3.1.1-17a–h A minimally invasive plate osteosynthesis wire passer set.
a Cerclage tunneling device.
b–c The cerclage passer closed (**b**) and open into two halves (**c**).
d–f The cerclage passer is placed around the bone in two separate pieces and then meets up at the end of the tube.
g Percutaneous wire cutter for cutting the wire through small incision.
h Trocar inserted in the tube of the passer to prevent soft tissue entering the tube.

2.2.3 Reduction with the aid of implants

An implant can be used as a reduction tool as well as providing fracture fixation.

A simple example of this is the reduction achieved by an anatomically shaped intramedullary nail. As the nail crosses the fracture from one fragment with the same diameter to the other, reduction in the coronal and sagittal planes must occur. In multifragment shaft fractures some lengthening can be obtained after distal interlocking by hammering the nail further distally. However, precise planning is needed with the measurement of the correct nail length on an x-ray of the entire opposite bone [17].

Reduction onto a plate

Fractures within a straight segment of the diaphysis may be reduced with a plate to restore alignment before definitive fixation (Video 3.1.1-11).

By distracting the fracture the tension in the soft tissues is increased, which tends to realign the fragments to their original position. The push-pull technique with a bone spreader and the Verbrugge forceps is an elegant way of distracting and reducing a fracture of, for example, forearm bones or in delayed surgery of a malleolar type B or type C fracture (**Fig 3.1.1-18**, **Video 3.1.1-12**).

Video 3.1.1-11 Reduction of an oblique fracture using the plate as a reduction tool.

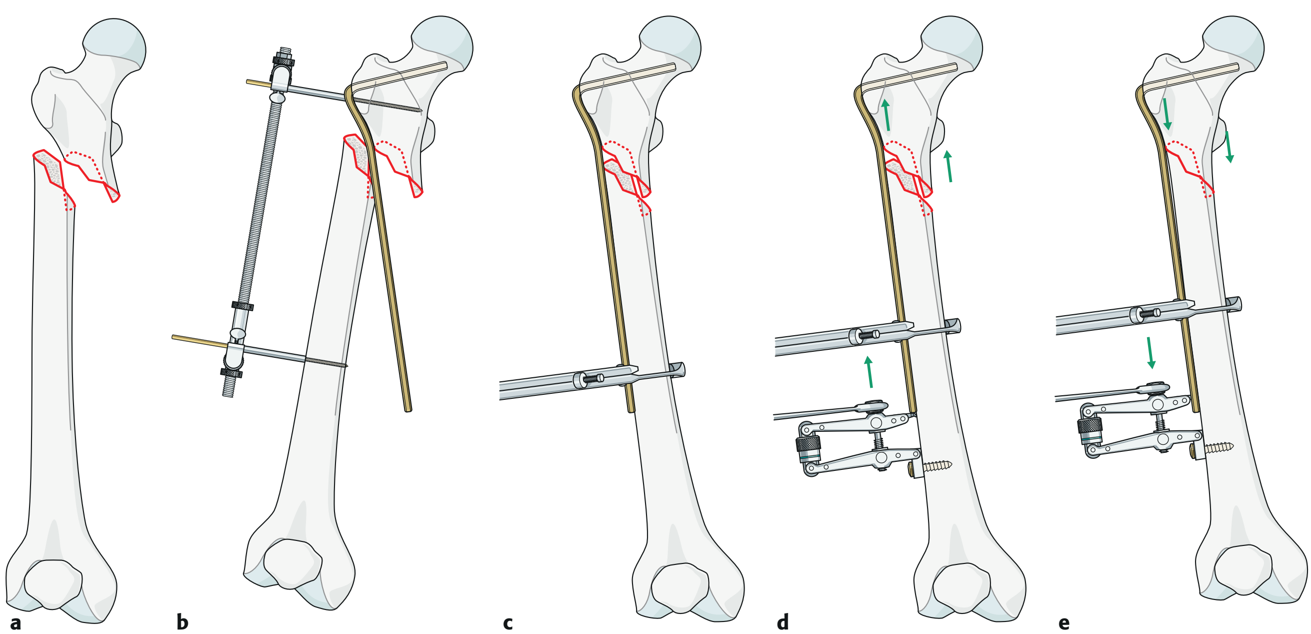


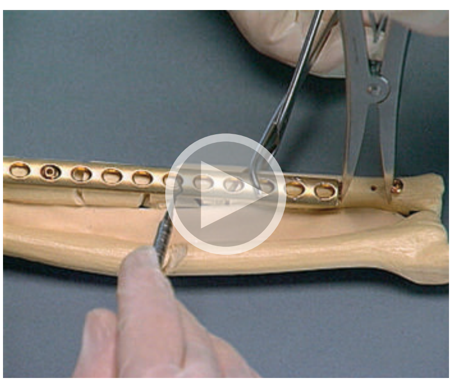
Fig 3.1.1-18a–e Reduction with the help of the condylar blade plate.
- **a** Displaced proximal femoral fracture with the proximal fragment in adduction and flexion.
- **b** Introduction of the 95° angled blade plate (condylar blade plate) and distraction of the fracture with the large distractor.
- **c** Provisional fixation with a reduction forceps distally.
- **d** Use of the articulated tension device to distract the fracture and to allow complete reduction proximally.
- **e** By reversal of the small hook, the tension device is used for interfragmentary compression.

Buttress/antiglide plate

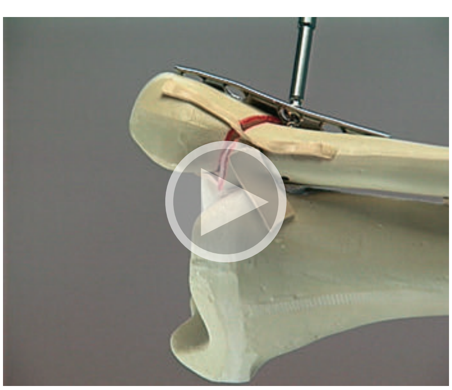
Another simple and powerful reduction mechanism uses the plate in buttress function. Applying a properly contoured plate to the diaphyseal fragment of an oblique metaphyseal fracture automatically reduces the fracture. This technique corrects small displacements and angulation while maintaining stability as the reduction occurs (**Fig 3.1.1-19**, **Video 3.1.1-13**).

Angled blade plate

An angled blade plate, when correctly inserted in the proximal or distal metaphyseal segment of the femur, will, by its shape, bring the diaphyseal segment into anatomical alignment. This technique is mainly used for deformity correction for malunions or nonunions (**Fig 3.1.1-18**).



Video 3.1.1-12 A bone spreader can be used to distract a fracture and allow reduction.



Video 3.1.1-13 Reduction of type B lateral malleolus fracture with a posterior buttress plate.

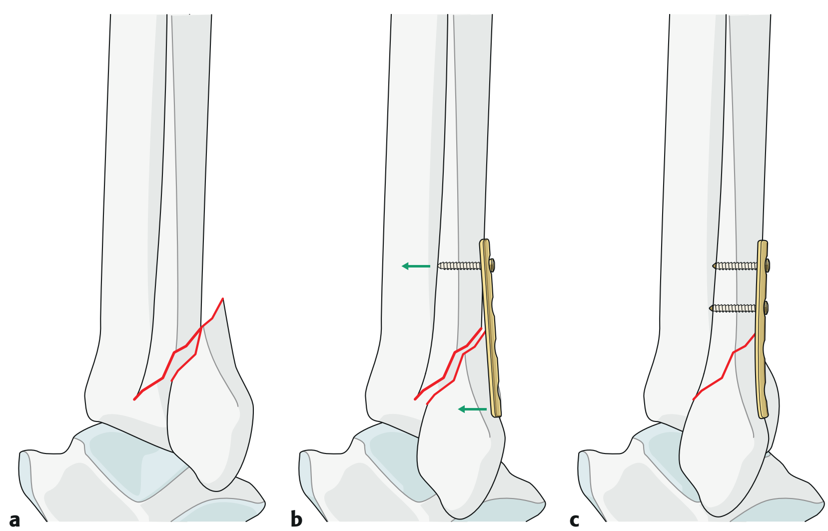


Fig 3.1.1-19a–c Indirect reduction with a plate functioning in buttress (or antiglide) mode.

a Posteriorly displaced fracture (type B) of the lateral malleolus.

b Fixation of a 4-hole or 5-hole one-third tubular plate posteriorly onto the proximal fragment.

c Tightening of the screw forces the distal fragment to glide distally and anteriorly along the oblique fracture plane into the correct position, where it is firmly locked by the plate. A lag screw may now be placed through the plate across the oblique fracture.

Anatomical contoured plates

The goals of reduction with this new generation of implants remain the same as with conventional plates. However, the application of these implants may be more demanding if they are used with submuscular or subcutaneous insertion in combination with indirect reduction techniques. Preoperative planning of the reduction, implant insertion, and order of screw placement is essential (**Figs 3.1.1-20–21**).

If conventional screws and locking head screws are to be used in the same bone segment, the order of screw insertion is important.

Miniplates and unicortical screws

The use of mini-fragment plates (2.7, 2.4, and 2.0) and screws to assist in reduction of long bone injuries in upper extremity fractures is increasing [18, 19], especially in complex periarticular injuries (see chapter 3.2.2).

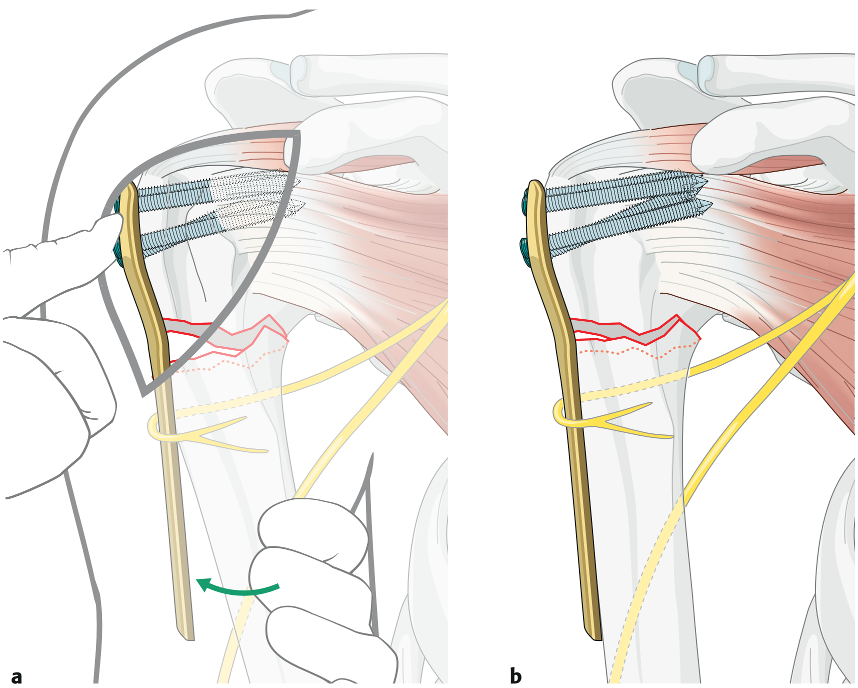


Fig 3.1.1-20a–b The anatomical plate is used as a reduction aid in the proximal humerus. Note that the plate is passed deep to the axillary nerve.

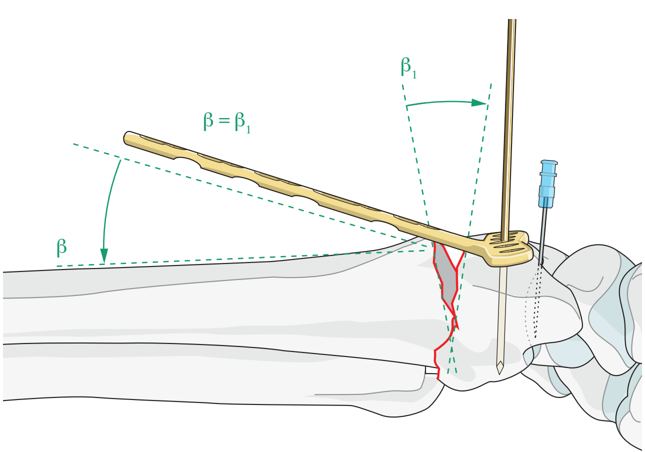


Fig 3.1.1-21 The anatomical distal radial plate is used as a reduction aid during an anterior (palmar) approach to the wrist. Careful planning of the reduction and plate placement is required. It must be noted that fixation must first be obtained distally before the reduction takes place and is followed by proximal fixation.

3 Assessment of reduction

Once the reduction of a fracture has been performed by either direct or indirect techniques, correct alignment and rotation must be checked.

There are various ways to do so (**Table 3.1.1-3**), including direct vision, palpation (digital or instrumental), intraoperative x-rays or image intensification, arthroscopy, as well as computer-assisted systems.

The small indentations or landmarks that are present in every fracture line must be aligned if the fracture is visible (jigsaw puzzle technique). When a fracture surface cannot be viewed directly, gentle palpation with a fingertip may be helpful, eg, on the quadrilateral surface in the pelvis to control reduction of an acetabular fracture. Similarly, an appropriate instrument, such as an elevator, may be used blindly to check the accuracy of reduction of an articular surface, eg, of the tibia plateau. Clinical assessment of axial and rotational alignment may be difficult and unreliable. It is, however, frequently needed, especially in closed intramedullary nailing.

Intraoperative control of fracture reduction and fixation should be done by image intensification or x-rays in two planes, even if direct reduction is performed. Angulation of the fracture may be difficult to appreciate within the limited operative field.

In articular fractures the use of arthroscopy has been described to assist or check reduction (eg, tibial plateau).

The latest developments include the use of computer-guided systems for the placement of instruments and implants or for localizing of bone fragments in space. Anatomical landmarks proximal and distal to a fracture site can serve as a reference for the calculation of residual (translational or rotational) displacement using mathematical algorithms. Navigated long-bone fracture reduction is becoming available with the use of dedicated software and trackers. This will allow rapid and accurate reduction with much less radiation exposure [20, 21].

Method of control	Field of application	Advantages	Disadvantages
Visual control of anatomy/ reconstruction	Articular/simple diaphyseal fractures (humerus/forearm)	Direct visualization, accurate	Exposure of fracture fragments, soft-tissue damage in exposure
Palpation	Acetabulum and pelvic fractures	Can be done in any fracture	Needs experience, less accurate than direct visualization
Visual control of limb	Alignment of extremity (lower)	Easy to do, can be assisted by image intensifier	Inaccurate, needs normal contralateral extremity
	Rotation of the extremity (clinical)	Compare to normal side, easy to do	Inaccurate, needs normal contralateral extremity
Intraoperative x-rays	Any fracture	Better imaging than C-arm; accurate in assessing alignment in shaft fractures	Time consuming
Image intensification	Any fracture, MIO techniques	Available, immediate evaluation	Limited field of view, increase radiation exposure
Iso C 3-D image intensifier (3-D)	Articular fractures	Accurate	Cost, time consuming, radiation exposure
CT scan	Assess articular fractures, rotation in shaft fractures	Accurate	Unavailable in most operating rooms
Arthroscopic control	Articular fractures	Accurate for articular surface	Experience, saline pumped into joint and soft tissues
Computer-assisted navigation	Articular fractures, pelvis, acetabulum, spine	Accurate, no radiation	Cost, time to learn technique

Table 3.1.1-3 Control of reduction.
Abbreviations: CT, computed tomography; MIO, minimally invasive osteosynthesis.

Classic references | Review references

4 References

1. **Mast J, Jakob R, Ganz R.** *Planning and Reduction Technique in Fracture Surgery*. 1st ed. Berlin Heidelberg New York: Springer-Verlag; 1989.
2. **Müller ME, Allgöwer M, Schneider R, et al.** *Manual of Internal Fixation.* 3rd ed. Berlin Heidelberg New York: Springer-Verlag; 1990.
3. **Schatzker J, Tile M.** *The Rationale of Operative Fracture Care.* 3rd ed. Berlin Heidelberg New York: Springer-Verlag; 1987.
4. **Marsh JL, Buckwalter J, Gelberman R, et al.** Articular fractures: does anatomical reduction really change the result? *J Bone Joint Surg Am*. 2002 Jul;84(7):1259–1271.
5. **Matta JM.** Fractures of the acetabulum: accuracy of reduction and clinical results in patients managed operatively within three weeks after the injury. *J Bone Joint Surg Am.* 1996 Nov;78(11):1632–1645.
6. **Olson SA, Matta JM.** The computerized tomography subchondral arc: a new method of assessing acetabular articular continuity after fracture (a preliminary report). *J Orthop Trauma.* 1993;7(5):402–413.
7. **Rhinelander FW.** Tibial blood supply in relation to fracture healing. *Clin Orthop Relat Res.* 1974 Nov-Dec;(105):34–81.
8. **Trueta J.** Blood supply and the rate of healing of tibial fractures. *Clin Orthop Relat Res.* 1974 Nov-Dec;(105):11–26.
9. **Wilson JW.** Blood supply to developing, mature, and healing bone. In: Sumner-Smith G,ed. *Bone in Clinical Orthopedics,* 2nd ed. Stuttgart New York: Georg Thieme Verlag; 2002:23–116.
10. **Volgas D, Harder Y.** *Manual of Soft-Tissue Management in Orthopedic Trauma.* New York: Thieme; 2011.
11. **Link BC, Rosenkranz J, Winkler J, et al.** Minimally invasive plate osteosynthesis of the distal femur. *Oper Orthop Traumatol.* 2012 Sep;24(4-5):324–334.
12. **Siegall E, Ziran B.** En bloc joystick reduction of a comminuted intra-articular distal radius fracture: technical trick. *Am J Orthop (Belle Mead NJ).* 2014 Aug;43 (8):351–353.
13. **Mouhsine E, Garofalo R, Borens O, et al.** Cable fixation and early total hip arthroplasty in the treatment of acetabular fractures in elderly patients. *J Arthroplasty.* 2004 Apr;19(3):344–348.
14. **Perren SM, Fernandez Dell'Oca A, Lenz M, et al.** Cerclage, evolution and potential of a Cinderella technology. An overview with reference to periprosthetic fractures. *Acta Chir Orthop Traumatol Cech*. 2011;78(3):190–199.
15. **Wähnert D, Lenz M, Schlegel U, et al.** Cerclage handling for improved fracture treatment. A biomechanics study on the twisting procedure. *Acta Chir Orthop Traumatol Cech*. 2011;78(3):208–214.
16. **Apivatthakakul T, Phaliphot J, Leuvitoonvechkit S.** Percutaneous cerclage wiring, does it disrupt femoral blood supply? A cadaveric injection study. *Injury.* 2013 Feb;44(2):168–174.
17. **Krettek C, Miclau T, Grün O, et al.** Intraoperative control of axes, rotation and length in femoral and tibial fractures. Technical note. *Injury*. 1998;29(Suppl 3):C29–39.
18. **Archdeacon MT, Wyrick JD.** Reduction plating for provisional fracture fixation. *J Orthop Trauma.* 2006 Mar;20(3):206–211.
19. **Oh JK, Sahu D, Park JW, et al.** Use of 2.0 Miniplate system as reduction plate. *Arch Orthop Trauma Surg*. 2010 Oct;130 (10):1239–1242.
20. **Khaler D.** Navigated long-bone fracture reduction. *J Bone Joint Surg Am.* 2009 Feb;91 Suppl 1:102–107.
21. **Khoury A, Beyth S, Mosheiff R, et al.** Computer-assisted orthopaedic fracture reduction: clinical evaluation of a second generation prototype. *Curr Orthop Pract.* 2011;22(1):109–115.

5 Acknowledgment

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3.1.2 Approaches and intraoperative handling of soft tissues

Ching-Hou Ma

1 Introduction

"Exposure is the key to surgery"—this age-old adage has been revised in modern surgery. No longer are large skin incisions and wide subcutaneous exposures considered acceptable practice in trauma surgery. The health of the soft tissues, which surround a fracture, is now recognized as a key to successful fracture healing. The extent and the degree of soft-tissue injury at the time of fracture play an important role in healing and are one of the important factors that determine the personality of the injury. Patient factors, including advanced age, smoking, and systemic diseases, such as diabetes mellitus and vasculitis, may also affect soft-tissue healing and careful identification of comorbidities is essential when dealing with fractures. Correct interpretation of the soft-tissue damage, profound knowledge of the anatomy and the blood supply to the soft tissues, careful planning of incisions as well as accurate handling of the soft tissues can help avoid further damage and reduce complications.

2 Anatomy and blood supply of soft-tissue layers

Bone, endosteum, periosteum, muscles with their surrounding fascial layer, subcutaneous tissue, including its superficial fascial layer (tela subcutanea) [1], and finally skin can be regarded as an anatomical unit.

The blood supply to all these structures is closely related and interdependent, so it is important to understand the complex network of blood vessels and the flow of blood to successfully plan a safe and correct exposure of a fracture.

The blood supply to the skin is provided by two main sources: a fasciocutaneous vascular system and a musculocutaneous vascular network [2]. The fasciocutaneous vascular system runs through structures, such as fascia or septa of muscles. The musculocutaneous vascular system consists of three kinds of vessels:

- Segmental arteries, which are in continuity with the aorta with regard to perfusion pressure, generally course underneath the muscles and are accompanied by a single large vein, and often by a peripheral nerve [3]. The radial artery is a good example.
- Perforating vessels, also known as true muscle perforators, pass through the muscle or septa and serve as connections from segmental vessels to the cutaneous circulation. These conduits or perforators have connections to supply the muscles with blood.
- Cutaneous vessels, which consist of:
  - Musculocutaneous arteries coursing perpendicular to the skin surface
  - Direct cutaneous vessels coursing parallel to the skin

The latter can be divided into fascial, subcutaneous, and cutaneous plexuses (**Fig 3.1.2-1**) [4].

The fascia of the muscle, which consists of a dominant prefascial and a subfascial plexus, is well vascularized. In contrast, subcutaneous tissue is a poorly vascularized adipose tissue, which is separated by a well vascularized and mechanically resistant superficial fascial layer [1] that includes the subcutaneous plexus. This fascia is well developed in the trunk and in the thigh. The skin is vascularized by a complex system of various horizontal plexuses on different levels, including the subepidermal, the dermal, and the subdermal levels (**Fig 3.1.2-1**).

The different horizontal vascular plexuses are interconnected by vertically oriented vessels that perforate the muscle, septa, and subcutaneous tissues. These vertically oriented vessels originate from the cutaneous and musculocutaneous vascular system.

In a horizontal extension, these plexuses form vascular territories, also known as angiosomes, which are composite units of skin and the underlying deep tissue supplied by their source arteries [5]. They are defined by the extent of connections of the source vessel before they anastomose with branches of adjacent source vessels.

To guarantee perfusion to the adjacent soft tissue, the surgeon has to be aware of two major facts before exposing a fracture site:

- Mechanism of injury and the energy involved
- Local angiosomes including anatomical relations of the perforator vessels

If these facts are not taken into account, there is a risk of underestimating the extent of the injury to the soft tissue. Direct injury and edema may reduce or completely interrupt collateral blood supply to the skin and so further surgical injury to perforating vessels may result in skin necrosis that would not occur during elective surgery on uninjured skin. Degloving injuries are a particular risk.

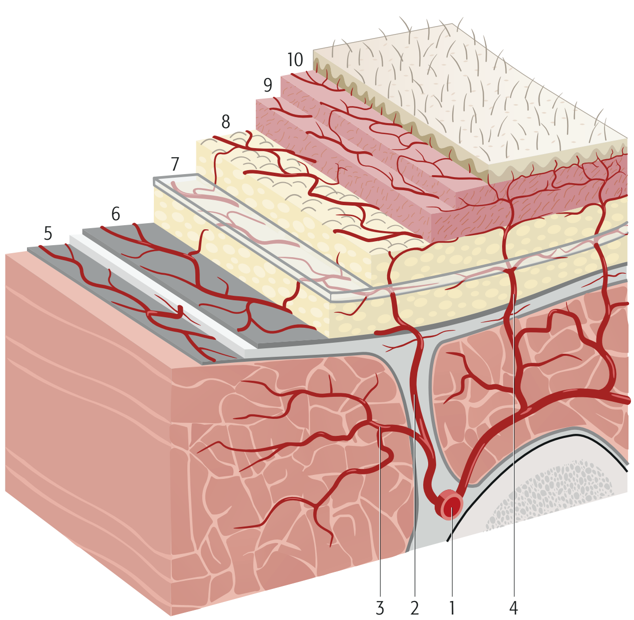


Fig 3.1.2-1 Cutaneous circulation.
The segmental artery (**1**) gives septocutaneous (**2**), muscular (**3**), and musculocutaneous (**4**) branches. The septocutaneous and musculocutaneous vessels perforate the deep fascia (the “perforators”). The cutaneous vessels consist of the perforators (**2**, **4**), which continue to run perpendicular to the skin. These give rise to three horizontal arterial plexuses: the fascial, which can be prefascial (**5**) and subfascial (**6**), the subcutaneous (**7**), and the cutaneous, which has three elements: subdermal (**8**), dermal (**9**), and subepidermal (**10**).

The surgeon must take care to avoid undermining the skin and to protect (vertical) perforating vessels during fracture surgery.

A wound must never be closed under tension, as this will reduce cutaneous blood flow and put the surrounding soft tissue at jeopardy.

3 Planning the surgical approach

The surgical approach will vary depending on the anatomical location of the injury, the type of reduction required, and the planned fracture fixation. In areas, such as the subcutaneous border of the ulna, where the skin is loosely attached to the underlying tissue and easily mobilized to cover a plate, a direct subcutaneous approach may be used. In other areas, such as the medial border of the distal tibia, the skin adheres tightly to the underlying structures and cannot be mobilized easily. Therefore, a subcutaneous approach may be much riskier. If the skin breaks down, the implant will be exposed and attempts to cover it by mobilizing local tissue will not be successful. Where possible, skin incisions should be sited over muscle. If there is skin break down with underlying muscle exposed, this can be covered by a skin graft.

Consideration should also be given to the following:

- Langer's lines (The result of elastic fibers within the dermis that serve to maintain the skin in a state of constant tension. They are a useful guide for the planning and designing of skin incisions.)
- Prevention of soft-tissue contracture (Curved or broken incisions should be used over skin creases overlying joints.)
- Anticipation of further surgery

For example, in periarticular knee fractures, delayed ligament repair or arthroplasty may be required, suggesting that straight incisions be used rather than curved ones. Likewise, an incision for plating of the fibula should be made more posteriorly to create a wide skin bridge if a second anterior approach is used to repair the distal tibial fracture at a later stage (**Fig 3.1.2-2**).

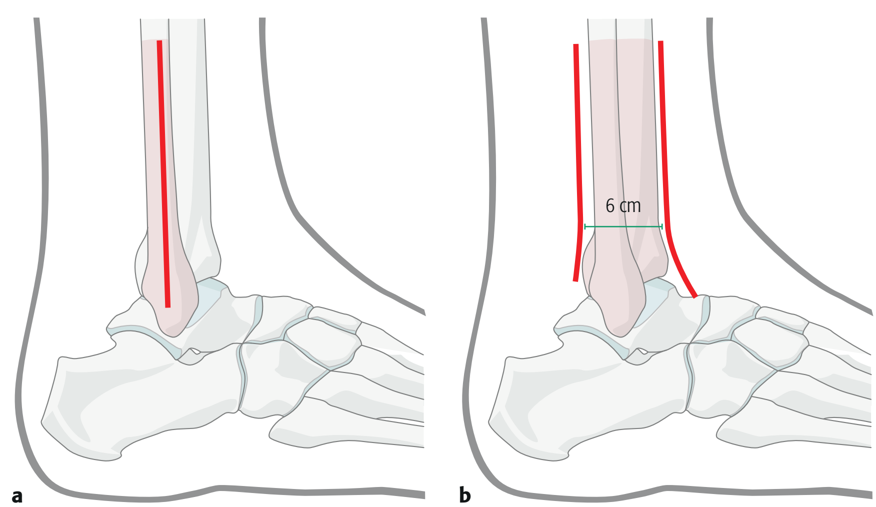


Fig 3.1.2-2a–b The standard incision for the lateral malleolus (**a**) must be moved more posterior if a second anterior approach to the distal tibia (**b**) is planned to allow a minimum skin bridge of 5–6 cm. The incisions must not undermine the skin margins.

4 Timing of surgery

There are several factors affecting the optimal timing of fracture fixation, the most important are:

- General condition of the patient, eg, polytrauma, acute comorbidities
- Soft-tissue injury
- Fracture reduction
- Planned rehabilitation

For each of these factors there may be a different optimal time for surgery and sometimes they are in conflict. Early fracture fixation allows earlier mobility of the limb and the patient, and reduces complications that are associated with prolonged immobilization, such as deep vein thrombosis and joint stiffness. Early surgery facilitates fracture reduction before the fracture becomes "sticky" due to callus formation and soft-tissue fibrosis. On the other hand, early fracture fixation may lead to increased wound complications if performed while the soft tissues are still traumatized and swollen. The amount of energy imparted on the tissues determines the zone of injury. This zone is characterized by disturbed microcirculation, which potentially endangers the viability of the soft tissues [6]. At the time of injury, it is often not possible to predict the extent of damage. Accordingly, the real area of traumatized soft tissue might be more extensive than initially appreciated, especially after high-energy trauma in the lower extremities.

The return of skin wrinkles shows that dermal edema has settled and is a favorable sign that soft-tissue swelling has decreased to the point where surgery can be undertaken safely. Gently pinching the skin or moving a neighboring joint (if possible) will demonstrate the presence or absence of skin wrinkles.

Fracture blisters are a problem for surgeons because they represent an injury to the dermis. There is little histological difference between blood-filled and clear blisters. Both are characterized by necrosis of the epidermis, although most surgeons are more concerned about blood-filled blisters [7]. There are many ways of treating fracture blisters while waiting for surgery. Removing the roof of the blister, followed by the application of various antibiotic ointments or Benzoin-tincture is advocated by some. Others leave the blister intact until surgery. No method is proven to be more beneficial than the other [7]. There is a consensus to delay surgery for 7–10 days for these types of injuries. If possible, incisions should avoid running through a blister and excessive retraction must be avoided.

As a rule, open reduction and internal fixation of the calcaneus, proximal and distal tibia can safely be postponed until 10–14 days after injury. In the upper limb, distal humeral fractures should ideally be repaired within 10 days. Elderly patients often benefit from early surgery and this has been established for hip fractures and may also be true for fractures in other sites, such as the proximal humerus [8]. The timing of fixation for fractures with associated compartment syndrome is difficult but early internal fixation in the upper limb is probably safe [9]. Most other fractures can be treated within 3 weeks from injury, if the soft tissues do not improve earlier. The patient should be counseled about smoking [10] and nutrition during this period when soft tissues are setting.

While waiting for surgery the fracture must be immobilized by a splint, by traction, or a temporary external fixator. This reduces not only pain but also significantly contributes to the recovery of the soft tissues. Moderate elevation of the extremity as well as foot compression devices—if applicable—help to resolve the swelling. Special attention must be given to the development of compartment syndrome (see chapter 1.5), especially if a circular splint or plaster cast has been applied.

A special and severe soft-tissue injury is the Morel-Lavallée lesion. It was originally described as an injury pattern associated with pelvic fractures where there is detachment of the skin and subcutaneous layers from deeper fascia. This type of lesion is caused by compression and shear stress at the transition zones of subcutaneous tissue and muscle fascia or the periosteum of bone as seen in run-over injuries. It leads to shearing of skin and subcutaneous tissue from the underlying muscle and/or bone, followed by the development of a blood-filled hollow space and fat liquefaction (**Fig 3.1.2-3**). If the skin remains intact, this closed degloving injury can persist for weeks or even months, and carries a risk of infection generally thought to be caused by hematogenous seeding. Up to 46% of closed degloving lesions may have culture positive aspirates before incision and debridement. The usual clinical appearance is a fluctuant mass with mobile skin and bruising but it may also present as a solid tumor that could be confused with neoplasm. Once opened, these cases carry a similar prognosis as full-thickness burns with risk of severe infection and skin necrosis.

Occasionally, the soft-tissue envelope does not return to a state that permits surgery. For example, some open fractures need flap reconstructions and the interval between first debridement and definitive fixation is lengthy. This will result in delayed rehabilitation and poor functional outcomes. Recently, a two-stage protocol has been designed for open tibial injury consisting of a first stage that used low-profile, locking plates for temporary fixation after debridement and reduction, followed by soft-tissue reconstruction [12–14]. The second stage then consisted of locking plates for definitive internal fixation, using minimally invasive percutaneous osteosynthesis. This protocol allows patients to start rehabilitation before definitive internal fixation. Decision making is key in these complex situations and the surgeon must weigh the risks of surgery against the complications of nonoperative treatment. There are times when nonoperative treatment is the best option because the patient's physiology, comorbidities, or soft tissues may never allow safe surgery. This course of treatment may be appropriate in older patients with poor nutrition or peripheral vascular disease or patients with severe multiple injuries who remain critically ill for a number of weeks.

Fig 3.1.2-3
a Soft-tissue injury to right thigh of patient with closed degloving (Morel-Lavallée).
b After surgical debridement.
c Negative-pressure wound therapy.

5 The incision and soft-tissue handling

Surgical dissection is a skill that is best learned by observing the techniques of experienced surgeons and by repeated practice. Careful attention to detail and observation of the following basic principles can help avoid many complications:

- **Time surgery carefully.** The risk of wound-healing complications is increased if extensive dissection is done in traumatized soft-tissue areas.
- **Remember that the blood supply to the skin comes from the underlying soft tissues.** Any dissection between the different planes endangers the blood supply. Dissection in high-risk areas should occur in a vertical direction and dissecting instruments must be oriented accordingly (**Fig 3.1.2-4**). Horizontal undermining will disrupt the vertical perforating vessels that supply the overlying skin.
- **Retractors must be used gently and sparingly.** Too much force applied to retractors may impede the capillary blood flow in the skin and disrupt perforating vessels. The assistant must be instructed to retract with gentle force and just to a point where the surgeon can see the area of interest. If excessive force is needed for the surgeon to visualize the fracture, it is often better to extend the incision and reduce the tension.
- **Retractors should be placed over, not beneath, the periosteum, especially Hohmann retractor on the opposite side of the incision.** Placing a retractor beneath the periosteum will result in considerable periosteal stripping, which must be avoided.
- **The use of forceps to hold the skin should be avoided.** If required the teeth of the forceps may be used to lift up the edge of the skin rather than to grasp it. This prevents undue squeezing of the delicate skin.
- **Sharp dissection leads to less tissue damage** than that caused by dull scalpels or blunt scissors. The creation of multiple planes of dissection by repeated attempts at exposing the fracture must be avoided.
- **Use meticulous hemostasis.** Poor hemostasis will result in hematoma or seroma and increases the risk of wound breakdown and infection. Finger pressure on the skin edges close to a bleeder will control bleeding and allow precise hemostasis focused on the actual vessel.
- **High-electrocautery settings that burn the skin edges must be avoided.** The indiscriminant use of electrocautery causes tissue necrosis and increases the risk of wound breakdown and infection.
- **Look for signs of soft-tissue damage during the approach.** Contusion of the subcutaneous fat or dermis indicates significant trauma to the soft-tissue envelope. Dead or questionably viable tissue must be excised.

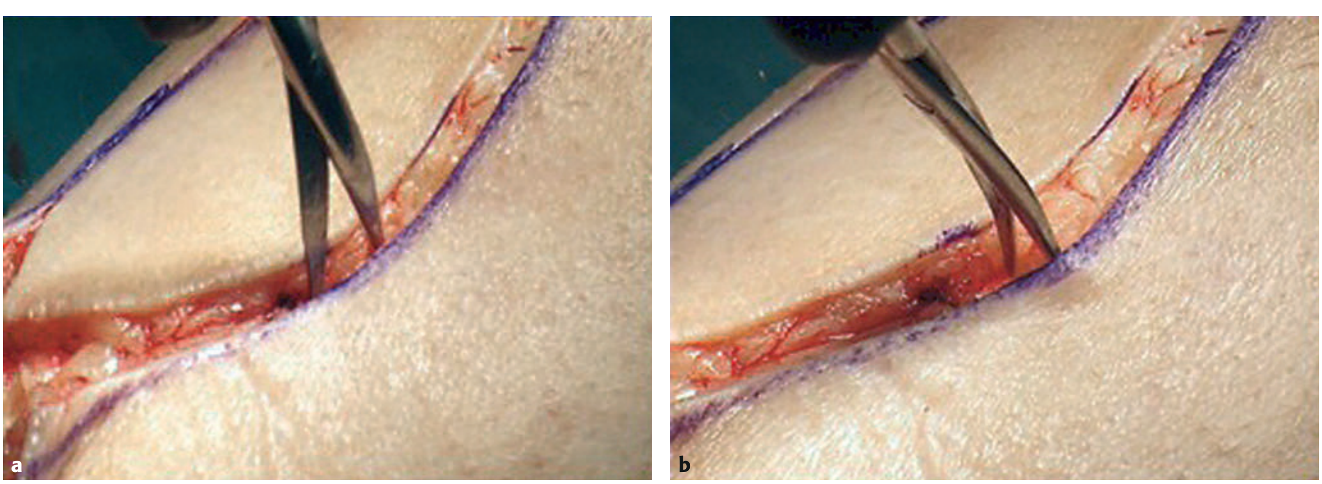


Fig 3.1.2-4a–b Dissection of subcutaneous tissue. This should always be in a vertical direction (**a**). Horizontal dissection that undermines the skin must always be avoided (**b**).

6 Incision and reduction technique

The type of reduction—direct or indirect (see chapter 3.1.1)—are important in determining the site and extent of the incision. There is a trend toward minimally invasive surgery in both acute and elective cases. Care must be taken that the planned incision allows satisfactory exposure, while minimizing any additional surgical insult (**Fig 3.1.2-5**).

The goal must be safe surgery, not the smallest possible incision.

It is better to use a larger incision than to use excessive traction that results in soft-tissue damage and necrosis. Repeated closed reductions or manipulation causes more tissue damage. Minimally invasive surgery is not indicated if the fracture cannot be reduced indirectly or in cases where there is a significant delay before surgery.

Diaphyseal fractures can often be approached through the muscle envelope, which may be significantly traumatized by the fracture from within. The approach must be gentle and respect the vascular supply to that area. In the humerus, the diaphyseal fracture often involves significant parts of the muscle envelope, which may facilitate the approach. Sometimes the surgeon must be prepared to modify the approach during surgery depending upon the "dissection" that has been produced by the fracture. Most muscles receive their blood supply and innervation from a proximal pedicle and care must be taken not to injure these structures.

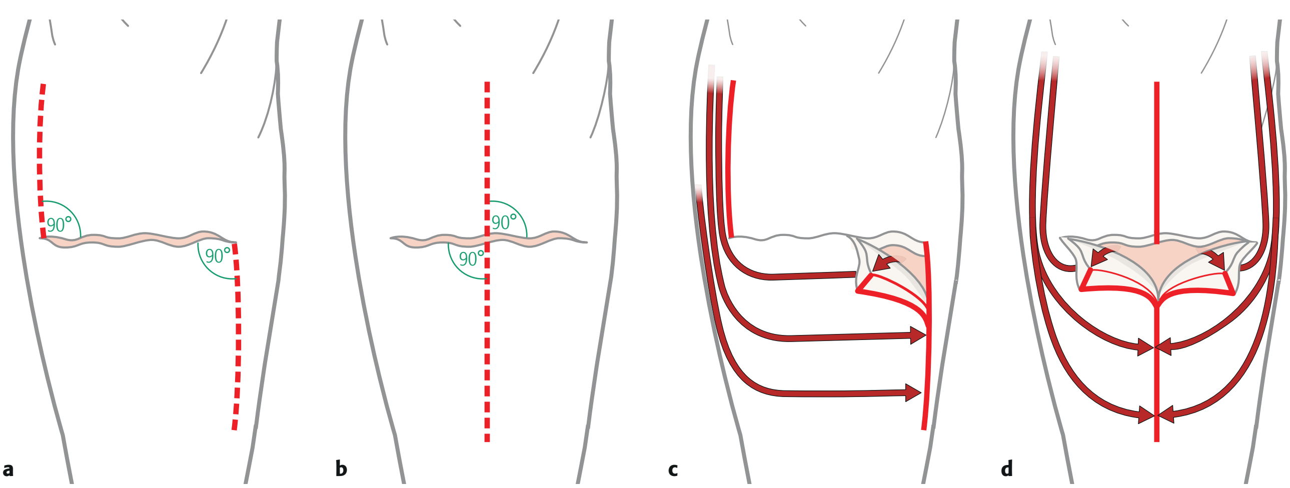


Fig 3.1.2-5a–d Management of a transverse wound.
a Transverse wound extended in a Z-fashion (red dotted line = planned incision).
b Transverse wound extended in a double opposing T-fashion (red dotted line = planned incision).
c Perfusion of a skin flap using a Z-like extension technique. Note that blood flow must traverse the entire zone of elevated skin flap (arrows).
d Perfusion of a skin flap using a double-opposing T-like extension technique. Note that the distance, which must be perfused (arrows) to reach the incision, is halved in comparison to that in **Fig 3.1.2-5c**.

The approach to metaphyseal and articular fractures should be carefully planned (**Fig 3.1.2-6**). Reconstruction of an articular fracture requires an open approach to allow a direct reduction. Associated metaphyseal comminution may be reduced indirectly and bridged by a plate that is inserted subcutaneously. Thus, an injury may be best treated by a combination of direct and indirect reduction to allow optimal soft-tissue handling.

7 Wound closure

The importance of wound closure must not be underestimated. This important part of fracture surgery should not be left to junior members of the team. Poor suture technique and misjudging the wound tension contribute to wound dehiscence. Poor placement of a splint or cast may also compromise the wound and so meticulous attention to detail is essential from the moment the patient enters the operating room to the moment he/she leaves.

Wound closure involves several basic principles:

- Wound healing depends on maintaining microcirculation and viable tissue at the wound edges.
- Excessive use of electrocautery may lead to poor vascularity at the skin edges.
- It is vitally important to keep the use of forceps to a minimum during suturing because crushing the skin edge will compromise the delicate vascular branches.

Fascial closure in the lower leg and forearm is not recommended for fear of compartment syndrome. If the subcutaneous tissue is badly contused, or if it is thin, a one-layer closure is preferable. In general, increasing the number of sutures will decrease the tension on a single suture. However, as the number of sutures increases, the local damage to subcutaneous tissue increases as there are more ischemic areas. The surgeon must rely on experience to determine the optimal tension for wound closure. A whitish area of skin between sutures is a sign of too much tension. Most surgeons do not advocate the use of a relaxation incision to

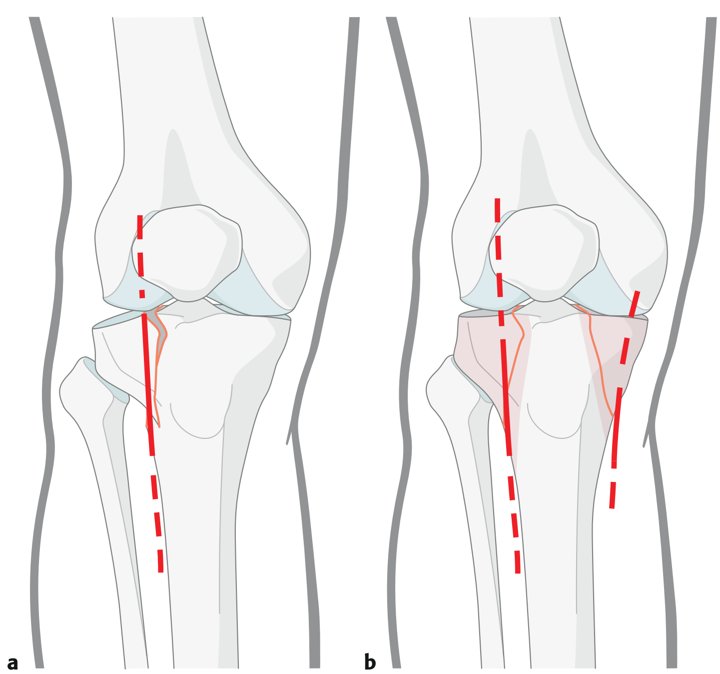


Fig 3.1.2-6a–b Approaches to proximal tibial fractures.
a The straight parapatellar approach is appropriate for proximal tibial fractures. It is extensile and does not compromise eventual secondary surgery.
b In more complex type C fractures, the medial condyle is best reduced and fixed via a separate posteromedial incision, while the lateral fracture is approached through an anterolateral approach. These two approaches are on opposite sides of the leg. The most delicate skin over the anterior and medial proximal tibia should not be touched.

allow wound closure with less tension. If the skin cannot be closed without tension then some form of primary reconstructive procedure will be needed (eg, skin graft or fasciocutaneous flap). Alternatively, the wound may be left open for delayed primary closure after swelling has resolved or a delayed reconstructive procedure [11] (**Fig 3.1.2-7**). These important decisions require experience.

The Allgöwer-Donati suture (**Fig 3.1.2-8**) is similar to a corner suture in that it enters the skin on one side of the wound, depicts a horizontal mattress on the far side of the incision, and then advances from deep to superficial at the end. It offers the advantage of grasping a relatively broad amount of tissue (thus spreading the tension force over a large area) while not disrupting as much of the vertical blood flow as a truly horizontal mattress. It is useful wherever there are flaps or parts of an incision that appear less vascularized than others. Furthermore, the Allgöwer-Donati suture technique—if properly applied—results in cosmetically acceptable scars [11] (**Video 3.1-1**).

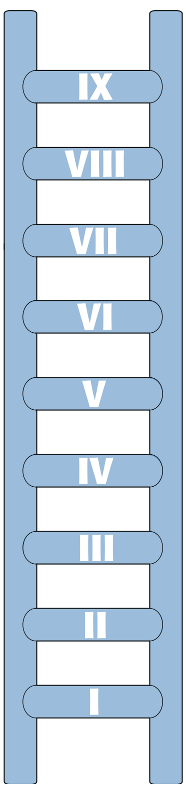


Fig 3.1.2-7 Classic reconstructive ladder. The simplest method that is likely to achieve stable closure or coverage should always be aimed at to avoid complications. The next rung is only climbed, if a simpler method fails. Primary, delayed primary, and secondary closure are not considered in this ladder. (Modified according to Ashton SJ, Beasley RW, Thorne CHM [1997] *Grabb and Smith's Plastic Surgery.* 5th ed. Philadelphia: Lippincott-Raven, 14.)

I Healing by secondary intention.
II Primary closure.
III Delayed primary closure.
IV Split-thickness skin graft.
V Full-thickness skin graft.
VI Tissue expansion.
VII Random pattern flap.
VIII Pedicled flap.
IX Free flap.

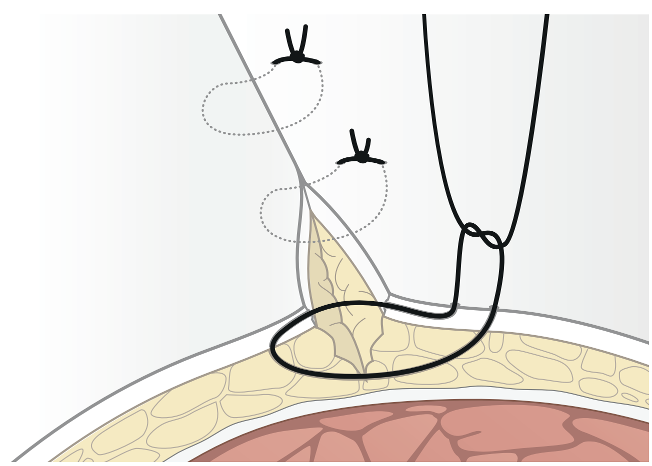
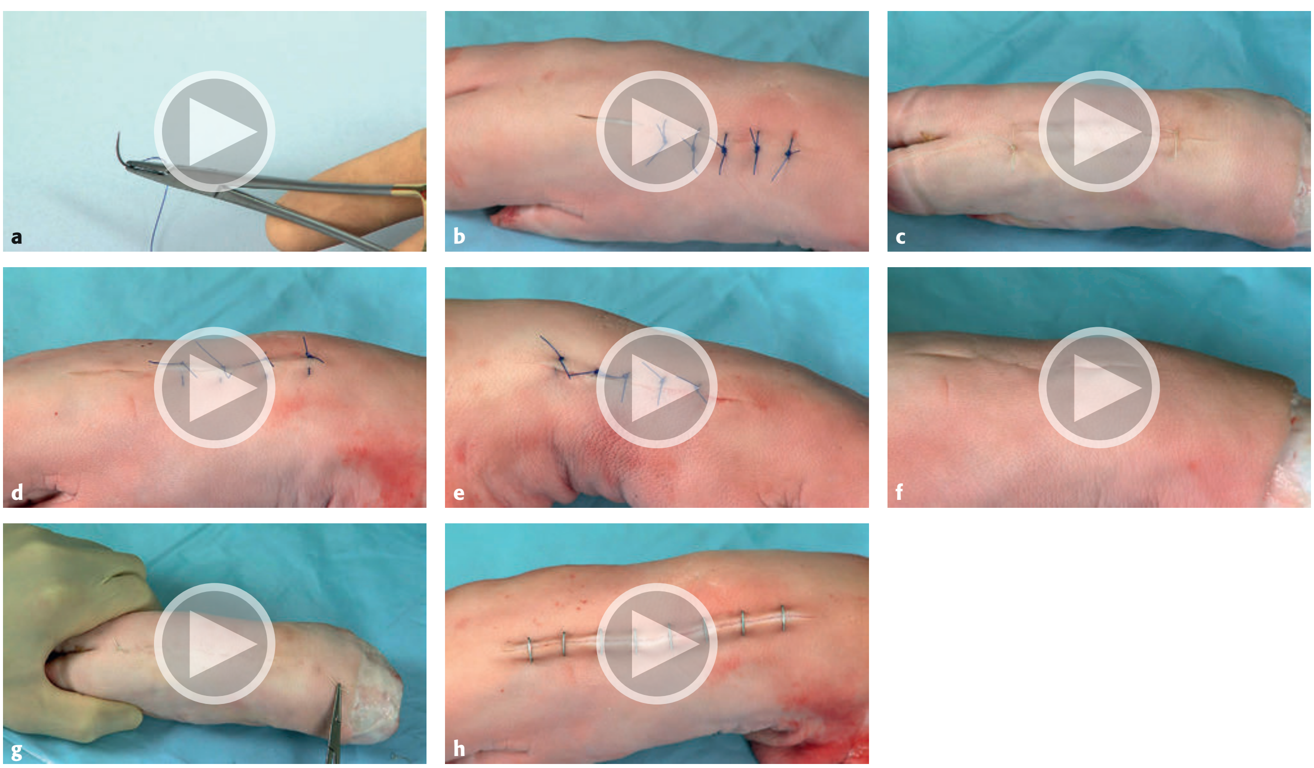


Fig 3.1.2-8 Allgöwer-Donati suture.

Another technique that may be useful in wounds that cannot be closed primarily is the use of silastic vessel loops to approximate the wound edges in stages (**Fig 3.1.2-9**) [15]. These prevent retraction of the skin edge and, as swelling decreases, the vessel loops pull the skin edges closer together. Antibiotic bead-pouch techniques can be used to enhance local antibiotic levels [11]. This can be done with wounds closed or left open (**Fig 3.1.2-10a–d**). Negative-pressure wound therapy [16] is useful in areas of skin loss and open fractures and promotes the rapid formation of granulation tissue. It may be combined with the silastic loop technique but is not advised when local antibiotic beads are used, as the vacuum effect removes the local eluted antibiotic.

Drains are a matter of personal preference with little evidence base for use. If they are used, active suction drains (vacuum) must be applied to aspirate any fluid accumulation in the wound, reduce any subcutaneous or submuscular dead space, and reduce bacterial contamination via the drain site. Because of the risk of infection, these drains should be removed within 24–48 hours. Drains are not a replacement for adequate hemostasis.



Video 3.1.1 Suture techniques shown on a porcine foot.

a General handling of instruments.
b Simple, interrupted suture technique.
c Simple, running suture technique.
d Vertical mattress (Donati) suture technique, interrupted and running.
e Allgöwer-Donati suture technique, interrupted and running.
f Simple, buried, interrupted suture technique.
g Intradermal, running suture technique.
h Skin closure with staples. There is level-1 evidence that skin staples should not be used to close wounds after hip fracture surgery in older patients.

Fig 3.1.2-9 Silastic vessel loops can be used to prevent skin retraction and facilitate delayed primary wound closure.

Fig 3.1.2-10a–d Antibiotic bead-pouch technique consisting of bone cement with 2.0 g vancomycin and 2.4 g tobramycin.

- **a** Clinical photograph of a Gustilo type IIIB fracture after debridement.
- **b** The edge of the wound is protected by first applying collodion or benzoin, and a thin rim of occlusive dressing in order to prevent maceration of the wound edges.
- **c** Small 5–8 mm beads strung on a suture are placed over the wound.
- **d** Coverage by an occlusive dressing.

Classic references **Review references**

8 References

1. **Nakajima H, Minabe T, Imanishi N.** Three-dimensional analysis and classification of arteries in the skin and subcutaneous adipofascial tissue by computer graphics imaging. *Plast Reconstr Surg.* 1998 Sep;102(3):748–760.
2. **Daniel RK, Williams HB.** The free transfer of skin flaps by microvascular anastomoses: an experimental study and a reappraisal. *Plast Reconstr Surg.* 1973 Jul;52(1):16–31.
3. **Daniel RK.** The anatomy and hemodynamics of the cutaneous circulation and their influence on skin flap design. In Grabb WC, Myers MB, eds. *Skin Flaps.* Boston: Little Brown; 1975.
4. **Daniel RK, Kerrigan CL.** Principles and physiology of skin flap surgery. In: McCarthy JG, ed. *Plastic Surgery.* Philadelphia: Saunders; 1990.
5. **Taylor GI, Palmer JH.** The vascular territories (angiosomes) of the body: experimental study and clinical applications. *Br J Plast Surg.* 1987 Mar;40(2):113–141.
6. **Yaremchuk MJ, Brumback RJ, Manson PN, et al.** Acute and definitive management of traumatic osteocutaneous defects of the lower extremity. *Plast Reconstr Surg.* 1987 Jul;80(1):1–14.
7. **Giordano CP, Koval KF.** Treatment of fracture blisters: a prospective study of 53 cases. *J Orthop Trauma.* 1995 Apr;9(2):171–176.
8. **Menendez ME, Ring D.** Does the timing of surgery for proximal humeral fracture affect inpatient outcomes? *J Shoulder Elbow Surg.* 2014 Sep;23(9):1257–1262.
9. **Blum J, Gercek E, Hansen M, et al.** [Operative strategies in the treatment of upper limb fractures in polytraumatized patients.] *Unfallchirug.* 2005 Oct;108(10):843–844. German.
10. **Sorensen LT, Karlsmark T, Gottrup F.** Abstinence from smoking reduces incisional wound infection: a randomized controlled trial. *Ann Surg.* 2003 Jul;238(1):1–5.
11. **Volgas D, Harder Y.** *Manual of Soft tissue Management in Orthopedic Trauma.* Stuttgart: Thieme; 2011.
12. **Ma CH, Tu YK, Yeh JH, et al.** Using external and internal locking plates in a two-stage protocol for treatment of segmental tibial fractures. *J Trauma.* 2011 Sep;71(3):614–619.
13. **Ma CH, Wu CH, Yu SW, et al.** Staged external and internal less-invasive stabilisation system plating for open proximal tibial fractures. *Injury.* 2010 Feb;41(2):190–196.
14. **Ma CH, Yu SW, Tu YK, et al.** Staged external and internal locked plating for open distal tibial fractures. *Acta Orthop.* 2010 Jun;81(3):382–386.
15. **Asgari MM, Spinelli HM.** The vessel loop shoelace technique for closure of fasciotomy wounds. *Ann Plast Surg.* 2000 Feb;44(2):225–229.
16. **Harvin WH, Stannard JP.** Negative-pressure wound therapy in acute traumatic and surgical wounds in orthopedics. *J Bone Joint Surg Am.* 2014 Aug 6;96(15):1273–1279.

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3.1.3 Minimally invasive osteosynthesis

Reto Babst

1 Introduction

Minimally invasive fracture treatment is not a new concept in operative fracture care. Percutaneous fracture fixation using external fixators and intramedullary nails were used at the beginning of the last century by the French surgeon Alain Lambotte and during World War II by the German surgeon Gerhard Küntscher. Common to both techniques was minimal access to the bone through small skin incisions and an indirect reduction technique that did not involve direct manipulation and visualization of the fracture site. The relative stability achieved by both stabilization concepts resulted in indirect bone healing by callus formation. The appeal of this minimally invasive approach to fracture fixation was not the small incisions leaving small scars but the biological advantage with minimal soft-tissue compromise at the fracture site, allowing for undisturbed fracture healing and less infection. Open reduction and internal fixation (ORIF) aiming for absolute stability may result in devascularization of individual bone fragments.

In the late 1980s the concept of not touching the fracture site, when applying a plate as an extramedullary splint, was introduced by Mast et al [1] using an open approach but indirect reduction techniques in multifragmentary metaphyseal fractures. They used the term "biological osteosynthesis", since this technique aimed not for rigid anatomical fixation but for restoration of length, axis, and rotation without compromising the vascularity of the fracture fragments. This resulted in secondary bone healing with ample callus formation allowing earlier weight bearing, and fewer secondary bone grafts and deep infections. The first attempts at percutaneous submuscular fixation with the introduction of a plate through a small skin incision was described by Krettek et al [2], applying a fixed angle plate to the distal femur. The last two decades has seen the introduction of new adaptations to plate technology with locking head screws (LHS). This has facilitated the surgical technique and the world wide spread of the minimally invasive plate osteosynthesis (MIPO) technique [3]. The application of these locking plates has also been helped by special reduction and introduction tools and by the development of anatomically preshaped plates [4].

2 Definition of minimally invasive osteosynthesis

Minimally invasive osteosynthesis (MIO) is the internal fixation of fractures using indirect reduction techniques through small incisions to reduce a fracture and to insert an implant remote from the fracture zone. Minimally invasive osteosynthesis therefore includes all types of percutaneous fracture fixation, such as external fixation, intramedullary nailing, percutaneous K-wire and screw fixation, as well as MIPO.

This chapter focuses on MIPO, while other MIO procedures like external fixation (see chapter 3.3.3), intramedullary nailing (see chapter 3.3.1), and percutaneous K-wire and screw fixation (see chapter 3.2.1) can be found elsewhere.

In general, the biomechanical concept used with MIO is relative stability. However, under special conditions, absolute stability with MIPO can also be achieved using percutaneous lag screws in combination with a protection plate.

3 Indications for MIPO

The option of minimally invasive plate application must always be balanced against other possibilities, especially intramedullary nailing. Both have similar biological advantages over conventional ORIF and require careful preoperative planning.

MIPO is used in the following cases:

- In metaphyseal fractures
- When soft-tissue conditions preclude an open procedure
- When the fracture pattern is not suitable for intramedullary nailing (intraarticular extension, narrow or deformed medullary canal)
- When other implants obstruct the medullary canal (arthroplasties, femoral nails)
- When a fracture involves open growth plates
- When a patient's general condition (eg, polytrauma, lung contusion) precludes additional systemic insults, such as intramedullary reaming

Plate osteosynthesis must also provide the correct biomechanical environment for the specific fracture pattern. For example, when plating a simple metaphyseal fracture, absolute stability is best using interfragmentary compression with lag screw fixation. This goal can be achieved in a percutaneous fashion using minimally invasive techniques but requires meticulous surgical planning and technique.

The balance between MIPO and open surgery must always be tempered by the principles of osteosynthesis and the skills and experience of the treating surgeon.

4 Preoperative planning for MIPO

Preoperative planning is of paramount importance with MIPO techniques because imaging of the fracture zone is only possible with the C-arm. Therefore, adequate positioning of the patient to provide good access for AP and lateral C-arm views is imperative. The surgeon should consider draping both legs free to provide the healthy leg as a template for intraoperative control of length, alignment, and rotation.

4.1 What does planning include?

The surgeon should consider:

- Position of the patient, surgeon, surgical assistant, and operating room personnel
- Specific instruments and implants
- C-arm location and draping, type of operating table (eg, radiolucent)
- Draping of patient
- Biomechanical fixation concept
- Surgical approach
- Surgical sequence
- Tactic(s) for reduction
- Fixation steps
- Closure and aftercare

Several questions should be answered before starting a MIPO procedure:

- Where are the danger zones or safe corridors in respect to the planned implant access?
- Should the fixation provide relative stability by using a bridge plate or is the fracture best treated with absolute stability with interfragmentary compression?
- How can reduction be achieved and maintained?
- How best to check for length, alignment, and rotation with the C-arm before fixation?
- Are the surgical assistants and instruments for direct and indirect reduction available?
- Is the C-arm available with a competent technician?
- Is there need for additional instruments to facilitate percutaneous reduction?
- Is there need to precontour the plate?
- How and when does the surgeon proceed when the original goal of MIPO cannot be achieved (back-up plan)?

4.2 Danger zones

A thorough knowledge of surgical anatomy is necessary to avoid damaging vital structures, such as nerves and blood vessels. Several danger zones must be considered when inserting and manipulating instruments and implants through small incisions without visual control of the endangered structures.

- Proximal humerus:
  - Axillary nerve passes 5–7 cm below the acromion tip, around the proximal humerus, coming from posterior to anterior.

- Humeral shaft:
  - Radial nerve passes from proximal posterior to distal anterolateral and then between the brachialis and brachioradialis muscle.
  - Musculocutaneous nerve passes beneath the biceps muscle along the anterior and medial brachialis muscle.
- Femoral shaft:
  - Superficial femoral artery runs from proximal anterior to distal posterior through the adductor canal at the junction of the middle and distal third of the femur and comes close to the medial and posterior femur shaft before emerging in the popliteal fossa.
- Distal tibial shaft:
  - Neurovascular bundle of the anterior tibial artery and the deep peroneal nerve are closely adjacent to the distal third of the tibia running from posterior to the anterior surface of the tibia.
- Medial malleolus:
  - Saphenous nerve and vein are at the level of the medial malleolus.

4.3 Reduction

Closed reduction

Closed reduction using indirect reduction is a main tenet in MIPO. This technique can be demanding when the fracture has to be reduced without touching the fracture site. The soft-tissue envelope together with traction forces alongside the limb axes are needed to counteract the deforming forces and to create a stable operative field for MIPO. Complete muscle relaxation by an anesthetist may also be needed. This should result in restoration of length, alignment, and rotation. Several instruments, like the traction table, one or two large femoral distractors [5] or an external fixator can create a stable operative field. The insertion of the plate, which is temporarily or definitively fixed to the distal or the proximal fragment, can also be used to align the fracture. Additional tools like bumps or radiolucent triangles can also help reduce the fracture. Schanz screws, percutaneous ball spike pushers, manipulators, collinear forceps (**Fig 3.1.3-1**) or intramedullary rods help to fine tune the reduction of the fracture and to maintain it for x-ray control before MIPO fixation.

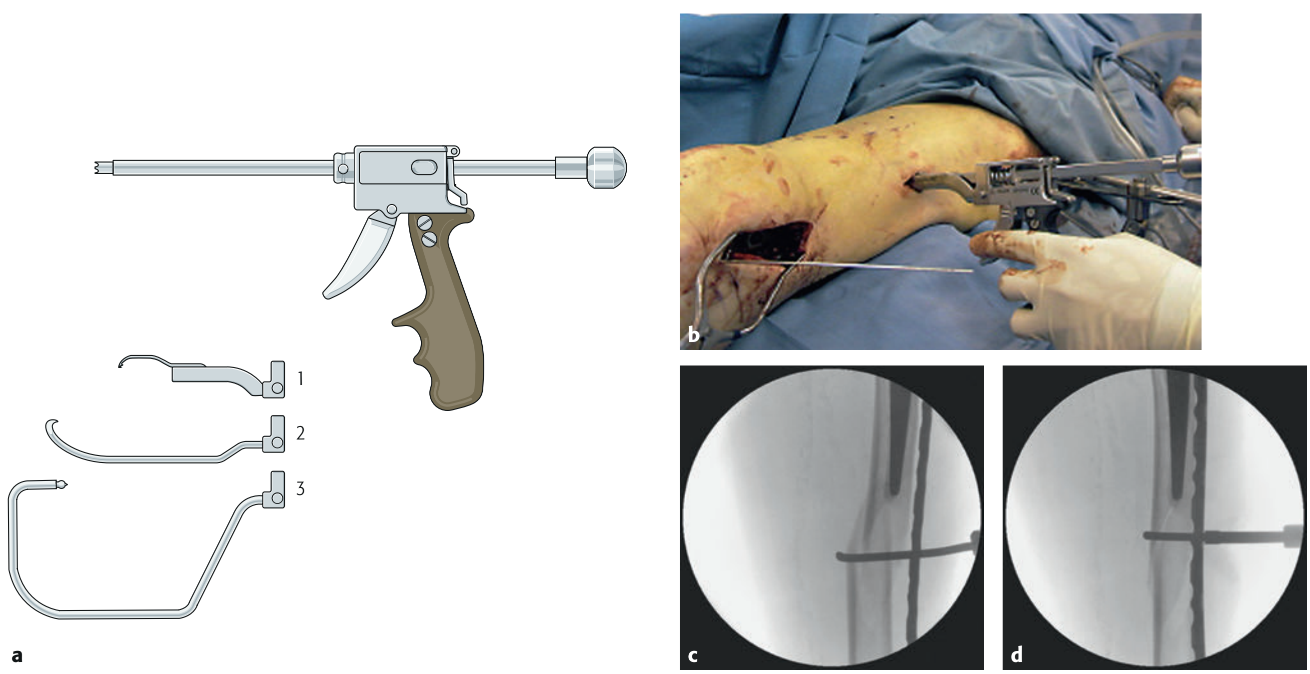


Fig 3.1.3-1a–d Collinear reduction forceps for minimally invasive percutaneous reduction of a periprosthetic fracture of the femoral shaft.

a Reduction forceps with different tips for minimally invasive plate osteosynthesis of shaft fractures (1). Pelvic and proximal femoral fractures (2) and articular fractures (3).

b Reduction forceps inserted through a short skin incision.

c Fracture reduction with collinear forceps in a periprosthetic fracture.

d Reduction of the distal fragment against the plate and holding the reduction with the collinear forceps.

Soft-tissue handling

The aim of MIPO is not to produce the smallest possible incision(s). Careful soft-tissue handling remains essential and excessive traction on the wounds must be avoided—it is better to extend the wound a few millimeters to facilitate insertion of the implant. Stretched and contused skin is prone to poor healing and wound infection. Subcutaneous plates must be carefully contoured and placed so they do not cause pressure necrosis of the wound. This can be a problem with tibial plates inserted at the medial malleolus.

Limited open reduction

Displaced intraarticular fractures and simple metaphyseal or diaphyseal fractures require anatomical reduction with lag screw fixation. This can be achieved by percutaneous manipulation using pushers, tamps and balloons for articular fractures under arthroscopic and C-arm control. For simple metaphyseal fractures, percutaneous applied clamps may provide anatomical reduction followed by insertion of a lag screw. A protection plate is then inserted through small incisions. In these situations, a limited open approach to achieve an anatomical reduction and stable fixation is recommended (**Fig 3.1.3-2**).

Role of cerclage in reduction

A cerclage is a simple and efficient centripetal reduction tool especially for simple spiral or oblique fractures and for the reduction of fragments around an implant (periprosthetic fractures). Historically, this technique developed a bad reputation but recent evidence has shown that when properly used with minimal soft-tissue stripping, it may be one of the best reduction techniques [6]. The method of application of the cerclage is vital. The periosteal blood supply must not be disturbed at the fracture site. A special forceps for minimally invasive application of cerclage wires allows for safe application of cerclage wires or cables for reduction of simple spiral fractures or additional fixation in periprosthetic fractures. The MIO wire passer is a special forceps with two connectable cannulated semicircles which can be inserted atraumatically around the bone. A wire or a cable can then be inserted with minimal soft-tissue damage (**Fig 3.1.1-17**).

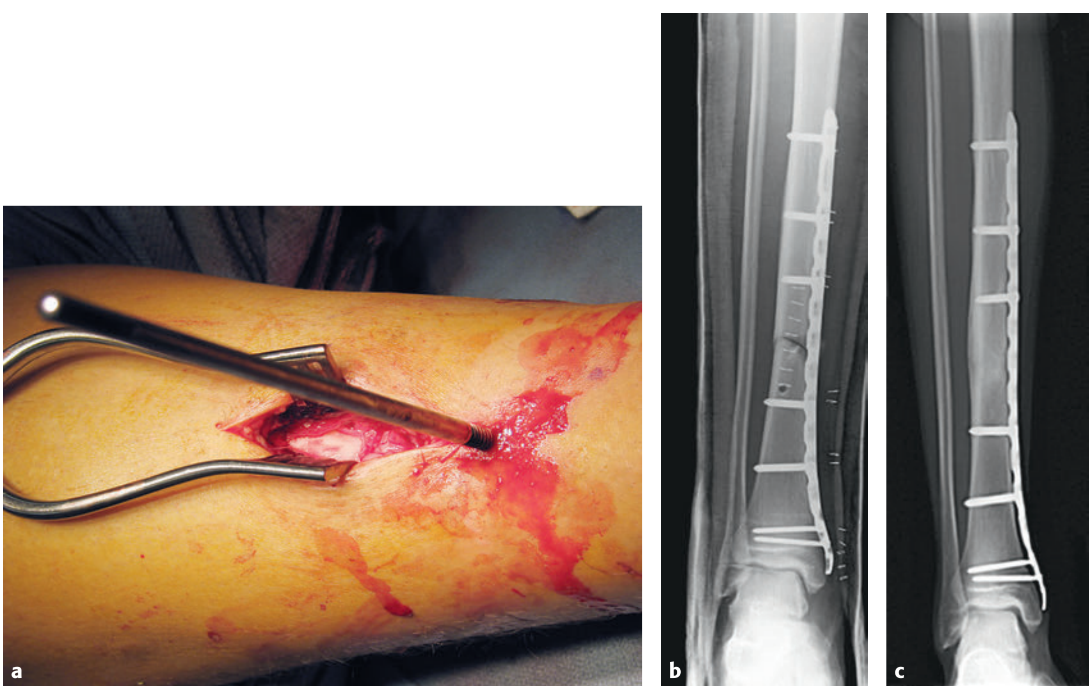


Fig 3.1.3-2a–c A 16-year-old patient with a simple fracture of the tibia.
a Closed percutaneous reduction with joystick (still in situ) did not give anatomical reduction, therefore a limited open approach to achieve anatomical reduction was performed before plate insertion.
b Postoperative x-ray: bridging plate concept. Note skin staples at the level of the incisions.
c X-ray 1 year postoperatively: bone healing with minimal callus formation.

4.4 Absolute or relative stability?

For most MIPO techniques, relative stability is the recommended biomechanical principle. The indirect reduction technique using long plates to bridge a multifragmentary metaphyseal or diaphyseal fracture is a classic example. This corrects length and alignment and allows undisturbed indirect fracture healing by callus formation.

However, the surgeon must be aware of rotational malalignment, as the literature shows a surprisingly high rate of this specific deformity (as high as 25% of cases) [7].

In contrast, simple metaphyseal or diaphyseal fractures (AO/OTA Classification type A fractures) require anatomical reduction and absolute stability obtained by interfragmentary compression using a lag screw and protection plate. This is the recommended principle to prevent high strain at the fracture gap and results in direct bone healing.

4.5 Implants

Minimally invasive plate osteosynthesis can be performed using many types of plates. Long straight plates are usually adequate for midshaft fractures. In recent years, anatomically preshaped locking compression plates (LCP) have become available.

Conventional plates (LC-DCP)

Conventional plates should be long (10–14 holes in the tibia and the humerus; 16–24 holes in the femur).

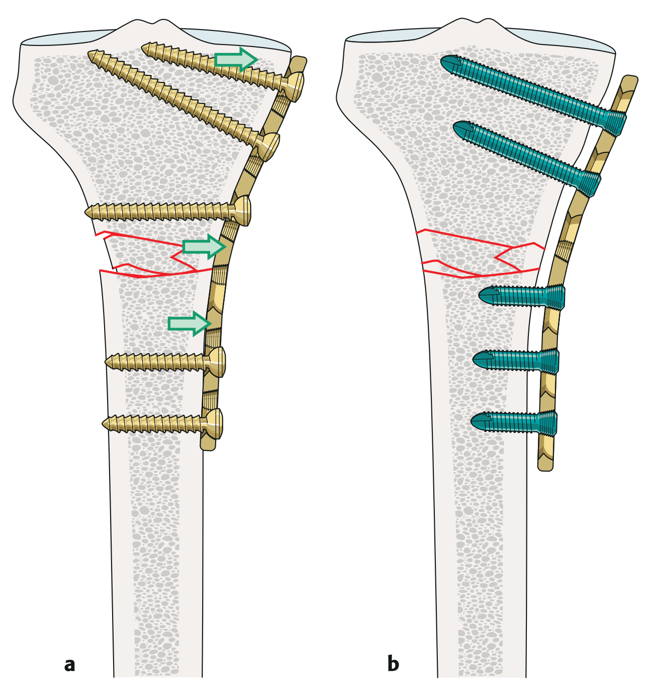
As a rule, the plate length should be three times longer than the fracture length.

The plate should reach from one metaphysis to the other [8]. Exact contouring of the plate is necessary to fit metaphyseal flares: conventional screws will bring the bone to the plate and if contouring is not precise, there will be a loss of reduction when the first screw is tightened (**Fig/Animation 3.1.3-3**). Precontouring the plate with a plastic bone model is helpful. This plate is sent for sterilization before the operation.

Locking compression plates

The LCP, if used as a locking plate, does not require a precise contouring. However, minimal contouring of straight LCPs (when not using anatomical plates) is advisable to prevent prominence of the plate under the skin.

Contouring of the LCP should not occur within the threaded holes as deformation may prevent purchase of the locking head screws.



Fig/Animation 3.1.3-3a–b

a With conventional screws the bone is reduced (pulled) toward the plate producing primary reduction loss when not precisely contoured.

b Angular stability of the locking head screws ensures maintenance of the initial reduction even if the plate is not contoured exactly. This allows the locking compression plate to be inserted by MIPO technique.

4.6 Intraoperative imaging

Without intraoperative imaging, MIO and MIPO are not feasible. An approach through soft-tissue windows remote from the fracture site with no direct visualization of the fractured fragments needs repetitive imaging to check the reduction. It is important to create a stable operative field, which allows maintenance of the reduction achieved. Fracture reduction can be maintained by indirect reduction tools like the traction table, the large femoral distractor, or the external fixator. Additional tools like bumps, towels, percutaneous clamps and K-wires are also helpful. This provides an environment where C-arm pictures in AP and lateral projection can be taken without radiation exposure of the surgeon's hands (see chapter 4.9).

4.7 Alternative plan

There should always be an alternative plan in case MIO/MIPO cannot be carried out as desired. This should include:

- Limited opening at the fracture site to apply an instrument for direct reduction
- Exposing the fracture as in conventional plating (ORIF)
- Asking for help from a more experienced surgeon

A thorough knowledge of the pros and cons of MIPO will help to reduce pitfalls associated with this demanding technique including malunion, delayed union, and nonunion.

4.8 Postoperative management

Postoperative management after MIPO surgery is not different from other MIO or ORIF cases. Pain medication may be required for a shorter time due to limited skin incisions. Antibiotic and thromboembolic prophylaxis is also mandatory like in other implant surgery. The affected limb should be well positioned and elevated and wrapped to reduce swelling. Splints will help to prevent contractures, eg, application of a U-slab to the ankle and the foot to prevent equinus. Physical therapy should be started as soon as possible after MIPO procedures. Joints should be mobilized by active or active-assisted movements or by passive continuous motion, especially after articular fractures. Weight bearing should be limited according to the fitness of the patient, the bone quality, and the fixation stability.

Implant removal may be considered after 1–2 years depending on the bone segment if:

- The patient is young
- When the implant is in the lower extremity
- When the implant limits limb function during work or sport or causes irritation

The patient should be informed about the possibility that broken screws may be left in situ because removal may cause soft-tissue and bone damage and increase the risk of refracture. When removing LHSs, special removal instruments should be available to remove jammed screw heads with conical extraction screws or special drill bits. To reduce the risk of refracture, patients should be advised to avoid contact sports or heavy labor for 2–4 months after implant removal [9].

5 MIPO in specific bone segments

Minimally invasive plate osteosynthesis has been shown to have some biological advantages in long bones when nailing is not an option, especially in periarticular fractures extending into the shaft. Recent literature [10–12] has shown the feasibility, safety, and efficacy of this technique. However, there remain some anatomical regions where MIPO is too dangerous for general application, such as the distal humerus or the forearm, due to the close proximity of the neurovascular structures [13]. In addition, MIPO may be used with scapula fractures [14], in the pelvis [15], in the calcaneus [16], and for corrective osteotomies [17] and bone transport [18].

5.1 Clavicle

Principle: Plate contouring and plate position is an important issue when deciding to perform MIPO of the clavicle. Superior plate position is easier to apply. The plate has to be bent in a horizontal S-shape fashion using a reconstruction plate 3.5 or an anatomical plate. Fixation of the plate is possible with conventional screws due to the flat surface of the clavicle. If anterior plate position is preferred, a vertical S-shape must be contoured or an anatomical plate is used. For anterior plate position, LCPs are preferred because they tolerate malcontour without compromising the achieved reduction. The fracture has to be reduced and stabilized either by a temporary plate or by a mini external fixator placed 90° to the definitive plate (**Fig 3.1.3-4**). The patient can be positioned in a supine or beach chair position. C-arm views in AP [10–12] are taken during the operation. Superior plate position causes more skin irritation than anterior position and is cosmetically less appealing in slim patients.

Patient selection: Simple clavicular shaft fractures are a good indication for MIO surgery with titanium elastic nails (ESIN, see chapter 6.1.2), whereas the indication for MIPO in clavicle fractures is multifragmentary clavicle fractures. Compared with ORIF, MIPO of midshaft clavicle fractures seems to be an effective fixation method (**Fig 3.1.3-4**) [19], but there may be a slightly increased risk of nonunion.

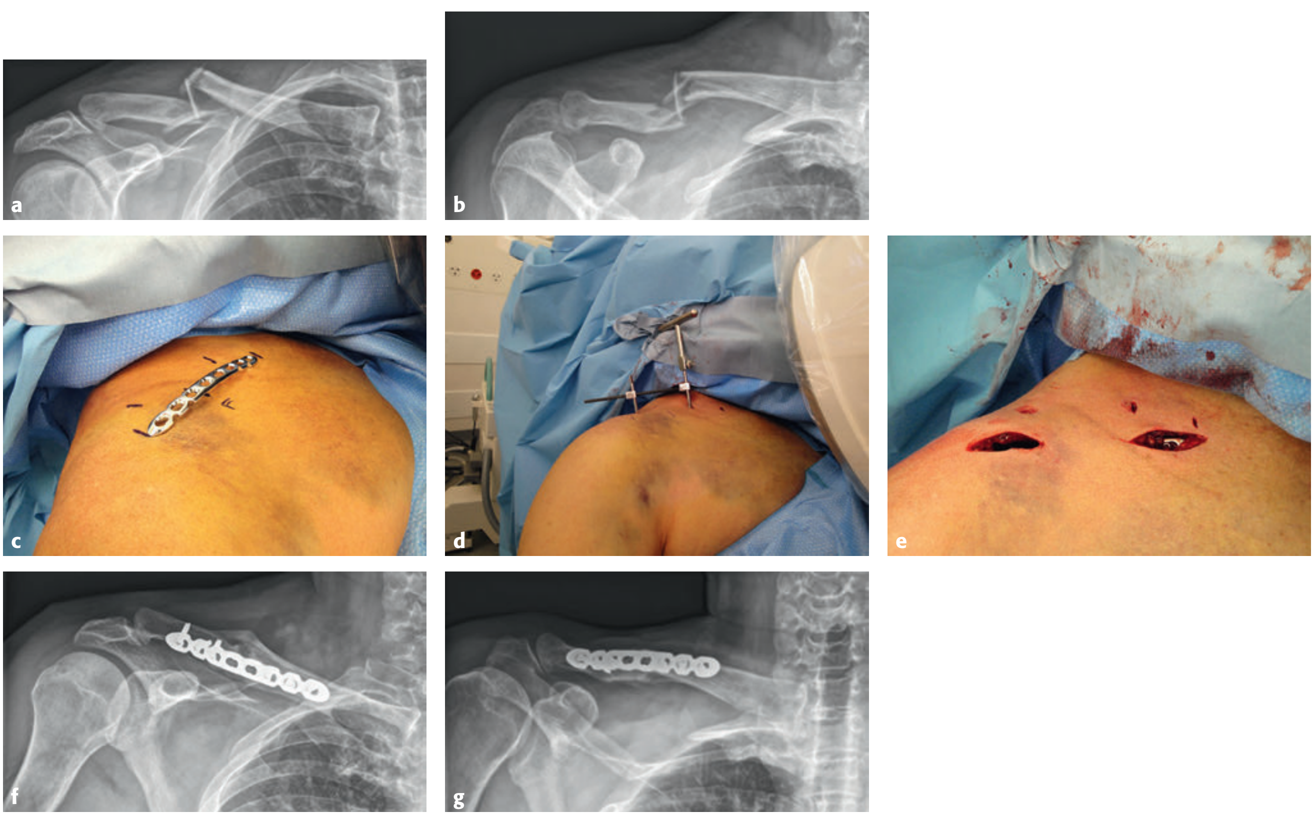


Fig 3.1.3-4a–g
a–b A 25-year-old patient with multifragmentary midshaft clavicular fracture.
c Due to fragmentation, a minimally invasive plate osteosynthesis anterior plating was chosen. Planning of incisions using the anterior plate.
d Reduction of the fracture with a superior small fragment external fixator.
e Soft-tissue windows after plate fixation.
f–g X-ray 1 year after operation.

5.2 Humerus

5.2.1 Humerus proximal

Principle: There are a multitude of anatomical plates for proximal humeral fractures available and these can be inserted using two MIPO approaches: either a short version of the conventional deltopectoral approach or a lateral deltoid-split where the plate is slid beneath the axillary nerve at the neck of the humerus. There is some recent evidence in favor of the MIPO approach [20]. Ligamentotaxis is of great help for reduction when using a beach chair position. Traction by an assistant or a pneumatic traction device (**Fig 3.1.3-5e**) reduces the fracture, which is then additionally stabilized by the inserted plate, temporarily fixed at the humeral head level, and then fixed at the shaft level (**Fig 3.1.3-5f–h**). The shaft is then reduced to the plate using a conventional screw before definitive fixation takes place. Intraarticular fractures that are not reduced by ligamentotaxis have to be reduced first by direct reduction through the fracture using an elevator before temporary fixation with K-wires. To neutralize the traction forces of the rotator cuff, stay sutures add stability when tied to the plate at the end of the fixation.

Patient selection: Displaced surgical neck fractures (11A2, 11B), including those with metaphyseal extensions, 3-part fractures (11B1 and 11B2), especially those with a large posterior major tuberosity fragment, and 4-part valgus impacted fractures (11C1) where soft-tissue attachments to the tuberosities remain intact (**Fig 3.1.3-5**). Fracture dislocations and grossly displaced fractures are difficult to reduce, so a formal deltopectoral or an extended lateral approach might then be chosen.

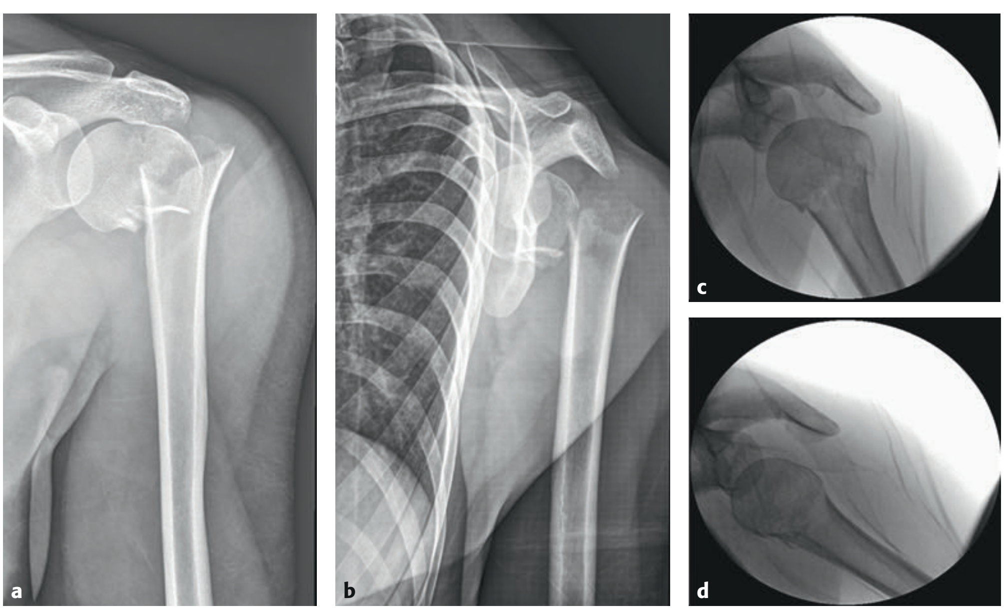


Fig 3.1.3-5a–l
a–b A 36-year-old patient with a displaced 2-part proximal humeral fracture.
c–d Intraoperative view after traction.

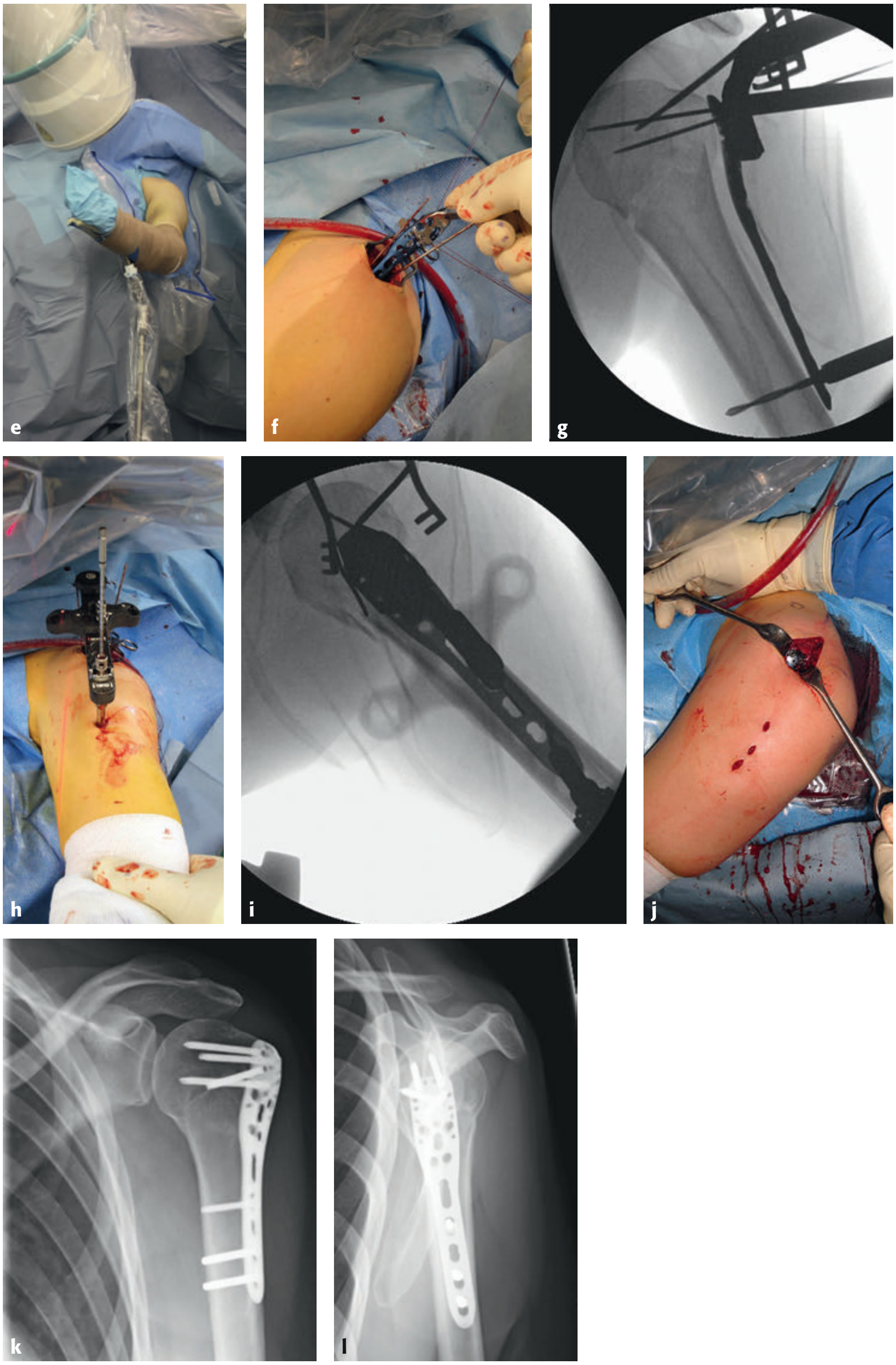


Fig 3.1.3-5a–l (**cont**)

e Pneumatic traction device to maintain reduction.
f Insertion of PHILOS plate.
g–h Temporary fixation of plate to the shaft using K-wires and a drill bit distal in AP view.
i X-ray control in axial view.
j–l Percutaneous definitive fixation of plate.

5.2.2 Humeral shaft

Principle: Fractures of the proximal and middle humerus need two different approaches when MIPO is used. Proximal humeral shaft fractures with fracture extension close to or into the humeral head are approached proximally by the same deltoid-split lateral approach as proximal humeral fractures. Depending on the fracture extension at the shaft level, the plate length determines the distal approach (**Fig 3.1.3-6**). This is determined by the course of the radial nerve and the decision of the surgeon to twist the MIPO plate or not. If the plate is not twisted, the incision is lateral and the radial nerve has to be explored, as it passes through the intermuscular septum between the lateral head of the triceps muscle and the brachioradialis muscle. The nerve will be in close relationship to the plate. If the plate is twisted then it will be positioned more anterolateral (twist ≤ 45°) or anterior (twist 70–90°) on the distal humeral shaft. For the anterolateral approach, the biceps muscle is retracted to the medial side and the brachialis muscle is split in the middle section, leaving a part of the brachialis muscle as protection for the radial nerve (**Fig 3.1.3-7**). A lateral straight plate helps fracture alignment and is technically easier to apply than a twisted plate. Patient position can be either supine using an arm table or in beach chair position using traction to stabilize the operative field. The inserted plate is temporarily fixed proximally to allow enough stability to check reduction with the image intensifier. An external fixator may be used to add stability to the operative field (**Fig 3.1.3-8c–d**).

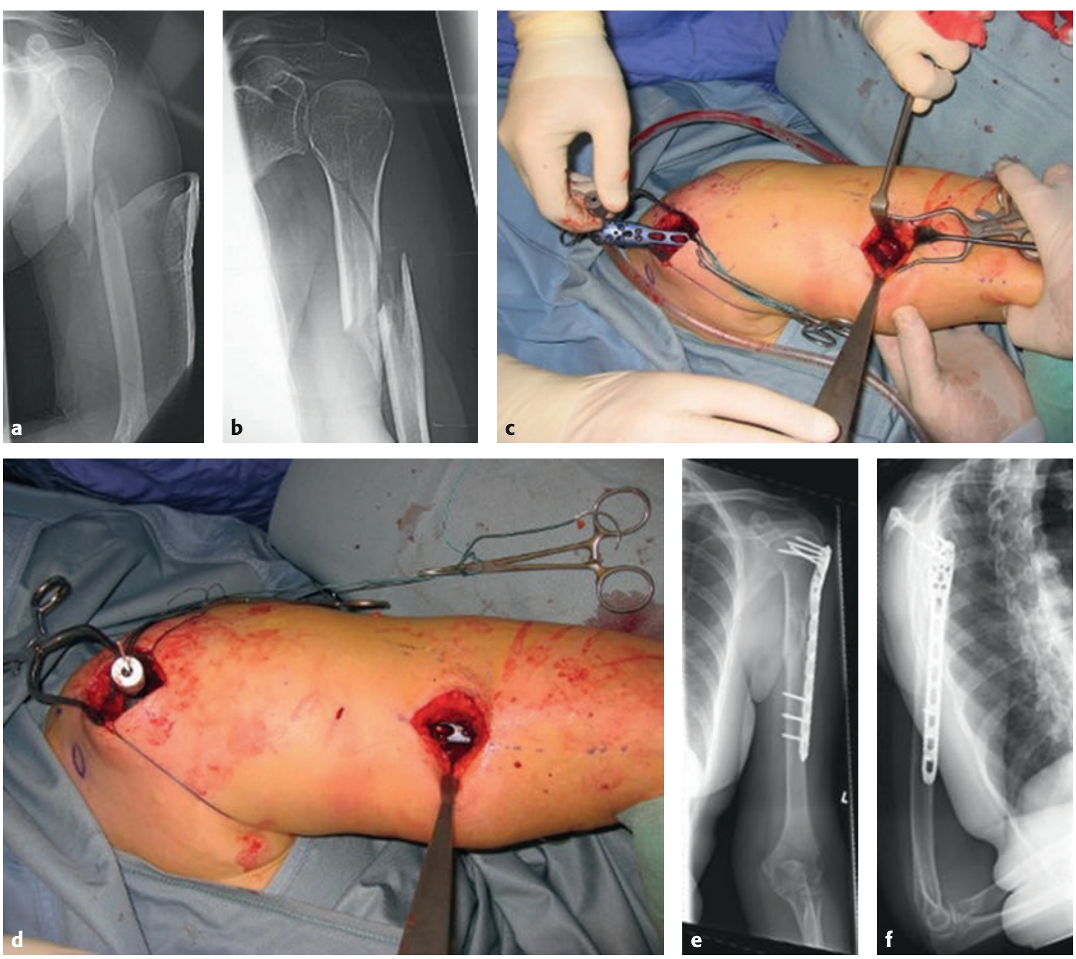


Fig 3.1.3-6a–f

- **a–b** A 66-year-old patient with a displaced proximal spiral humeral shaft fracture. Insertion of a straight PHILOS plate.
- **c** The distal incision was proximal to the anterior course of the radial nerve. Note stabilization of the operative field by traction.
- **d** Temporary fixation of the plate for C-arm control.
- **e–f** X-ray control 1 year postoperative.

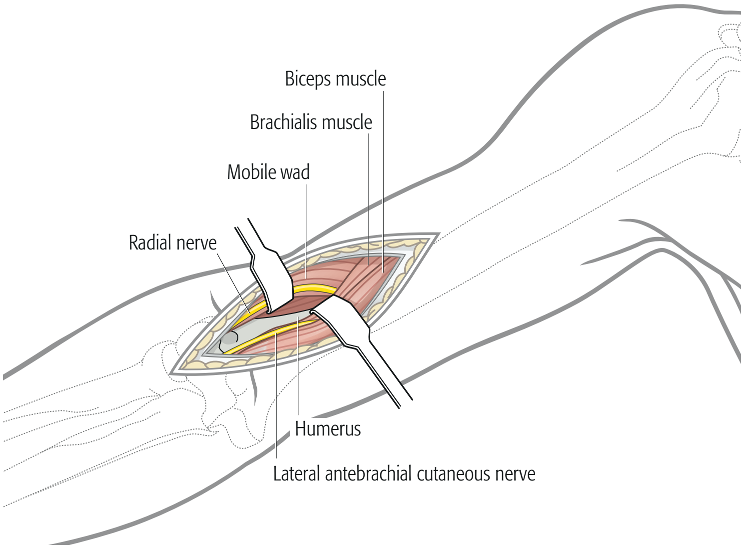


Fig 3.1.3-7 Anterolateral distal incision for distal plate fixation for a humeral midshaft fracture. The biceps muscle including the lateral antebrachial cutaneous nerve is pulled to the medial side. The brachialis muscle is split in the middle. The lateral part then serves to protect the radial nerve.

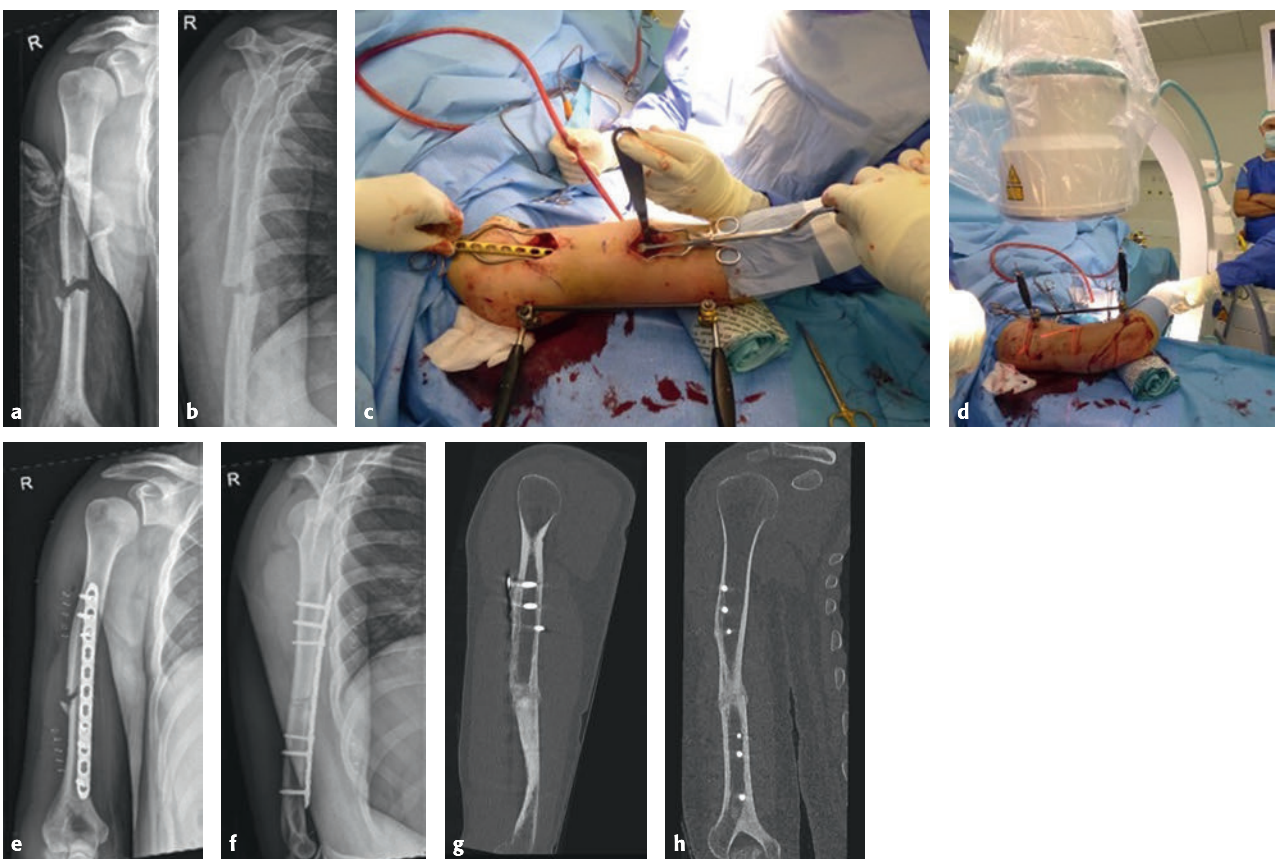


Fig 3.1.3-8a–h

a–b A 33-year-old patient with a distracted humeral midshaft fracture (12A3)

c The fracture was reduced and stabilized using the minimally invasive plate osteosynthesis manipulators combined with an external fixator rod. Insertion of the plate from proximal to distal using the epiperiostal surfer to pull the plate from proximal to distal.

d Lateral x-ray control of the reduction.

e–f Postoperative AP and lateral x-ray. Note the conventional screws close to the fracture as reduction screws and locking head screws at both plate ends. The fracture was fixed in slight distraction on the lateral side.

g–h The fracture was bridged by callus at the posteromedial cortex and the patient was fully weight bearing as a heavy manual worker 6 months after the operation.

Humeral midshaft fractures can be stabilized through an anterior approach using long, conventional narrow plates 3.5 or 4.5 according to the bone diameter. Because of the wide rotational excursion of the upper extremity, a long plate provides much more stable fixation than a short plate. Plate contouring is minimal in the distal part when using conventional screws and it is not necessary when using locking screws alone. The patient is preferably positioned in a supine position with an arm table in slight abduction to obtain a stable operative field. In the distal soft-tissue window, Hohmann retractors should not be used to avoid traction on the radial nerve. The long plate, spanning most of the length of the humerus, is then fixed with three screws in each fragment (**Fig 3.1.3-8**). Minimally invasive plate osteosynthesis of humeral shaft fracture has been shown to be a safe and reliable technique with similar results as conventional ORIF [21].

Patient selection: MIPO is a good indication for:

- Multifragmentary humeral shaft fractures extending proximally and distally
- Segmental fractures
- Small medullary canal, which does not allow nailing
- Shaft deformation due to earlier fracture
- Patients with open growth plates

Minimally invasive plate osteosynthesis is not recommended in delayed cases with significant shortening or in nonunions. Simple fractures are much more challenging to reduce and suboptimal reduction may lead to delayed healing or nonunion with implant failure and are better treated with anatomical reduction and compression plating to provide absolute stability.

5.3 Femur

5.3.1 Femur proximal

Principle: Many fixation devices are available for the treatment of proximal femoral fractures, eg, intramedullary and extramedullary implants. Extramedullary implants include the dynamic hip screw (DHS), the dynamic condylar screw (DCS), the 95° blade plate, the proximal femur locking compression plate (LCP-PF), and the reversed distal femur LCP (LCP-DF). According to the fracture pattern an intramedullary or an extramedullary implant may be preferred. Reduction is performed using a traction table in a supine position, or with the large femoral distractor or external fixator (**Fig 3.1.3-9**) when using a MIPO approach.

Patient selection: The role for MIPO in proximal femoral fractures is limited to:

- Trochanteric fractures with proximal extension involving the nail entry point
- Ipsilateral neck and complex shaft fractures not suitable for an intramedullary device
- Open subtrochanteric fractures

Open reduction and internal fixation in this region has been associated with a significant risk of nonunion and implant failure. Minimally invasive plate osteosynthesis has been shown to reduce the incidence of nonunion and the need for primary and secondary bone grafting [22].

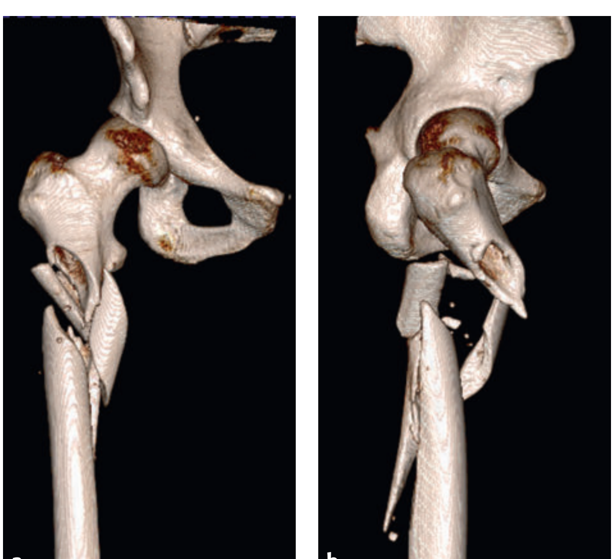
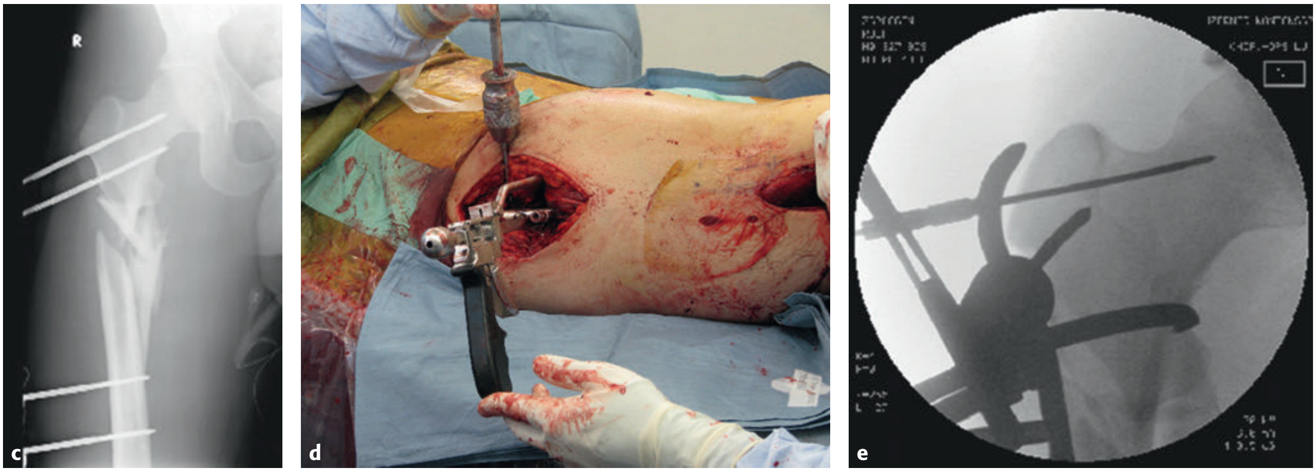


Fig 3.1.3-9a–h
a–b A 22-year-old polytrauma patient with a multifragmentary subtrochanteric fracture.



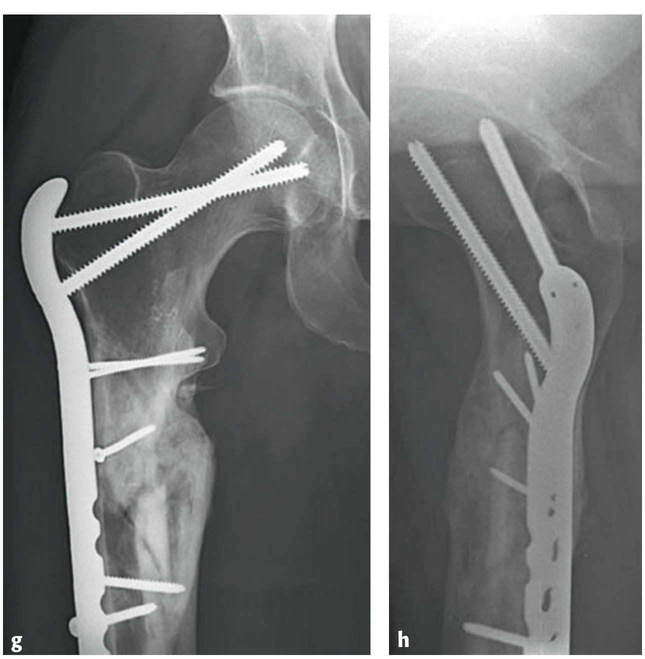


Fig 3.1.3-9a–h (cont)

c Damage-control surgery with external fixator.

d Through a proximal soft-tissue window the proximal fragment is reduced using a Schanz screw with a T-handle to neutralize the flexion forces of the iliopsoas muscle, an proximal femur locking compression plate was inserted and the proximal fragment was reduced using the collinear forceps against the LCP-PF.

e Intraoperative C-arm image with the proximal fragment reduced against the plate and temporary fixation with a K-wire and the collinear reduction clamp.

f Intraoperative clinical control for rotation. Length was controlled using the contralateral leg and the alignment is controlled by C-arm with the help of the cable method.

g–h X-ray control 1 year after trauma.

5.3.2 Femoral shaft

Principle: For MIPO of the femoral shaft, the broad dynamic compression plate (DCP), the low-contact dynamic compression plate (LC-DCP), or the LCP is available. The contoured LCP with antecurvature is helpful for MIPO fracture fixation due its sagittal bend. The patient is positioned on a radiolucent table with both legs draped free and a bump underneath the knee joint. There are two methods to achieve a stable operative field when performing MIPO of the femoral shaft.

- The plate is used as a reduction tool by proximal and distal temporary fixation in the center of the lateral cortex (**Fig 3.1.3-10**).
- The femoral shaft is reduced first using an external fixator or the large distractor before inserting and fixing the plate to the bone.

It is recommended to use at least three percutaneously inserted screws in the proximal and distal fragments. The plate length in multifragmentary fractures is usually 16–18 holes, whereas plates in simple fractures (which require anatomical reduction and absolute stability) have a length of 8–10 holes with a plate/screw density of 0.5.

Patient selection: Femoral shaft fractures (32B and 32C) are good indications for MIPO if:

- The femoral shaft is narrow or deformed.
- The pediatric patient has open physes.
- The medullary canal is occupied by an implant.
- General condition or associated fractures do not allow intramedullary nailing.

5.3.3 Femur distal

Principle: Several implants are specially designed for distal femoral fractures like the 95° blade plate, the distal femoral locking plate (LCP-DF), and the distal femoral nail. Intraarticular distal femoral fractures need absolute stability and are addressed first using a parapatellar approach to perform anatomical reduction of the joint surface. In extraarticular fractures, a soft-tissue window centred on the lateral femoral condyle is sufficient for plate insertion. However, the approach should be big enough to allow proper positioning of the implant. The patient is placed on a radiolucent table, with the contralateral leg draped free to compare length, alignment, and rotation after reduction of the joint block to the shaft. The reduction can be obtained by temporary fixation of the plate distally by using the plate as a reduction

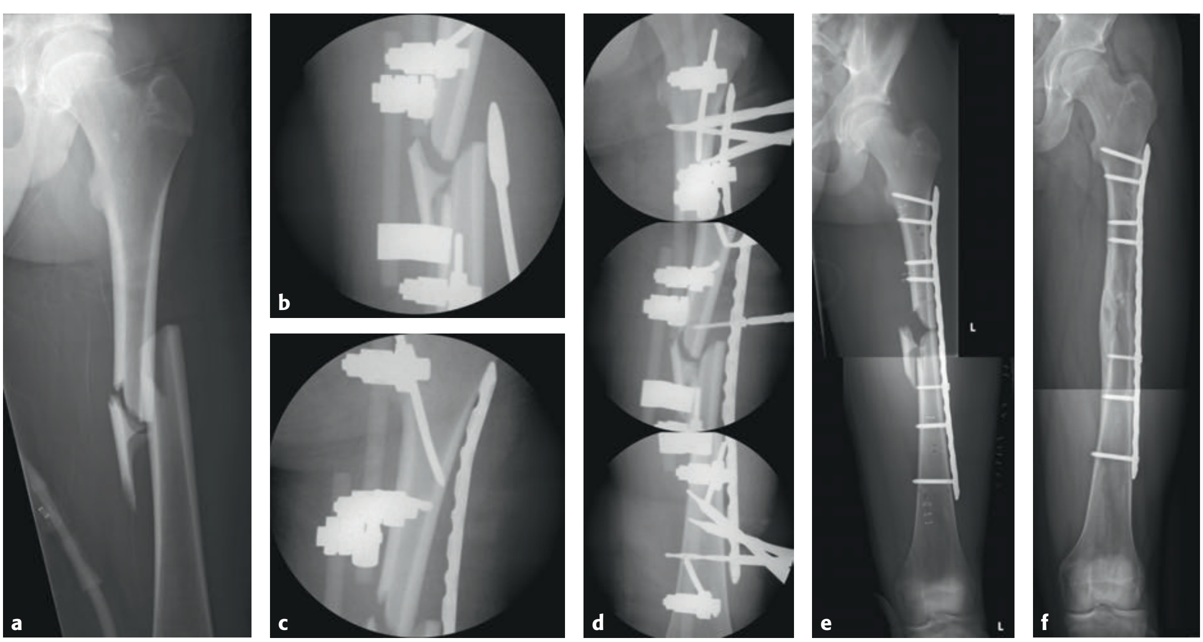


Fig. 3.1.3-10a–f

- **a** A 17-year-old polytrauma patient with narrow femoral canal, damage-control surgery with external fixator.
- **b** Remote from the fracture focus, a submuscular epiperisotal surfer was inserted and a submuscular tunnel was prepared.
- **c** The plate was inserted and aligned with the fracture.
- **d** The fracture was temporary fixed with drill bits through drill sleeves inserted in the threaded holes of the locking compression plate positioned in the center of the shaft. The intermediate fragment was reduced with a reduction screw.
- **e** AP x-ray postoperative. Apart from the reduction screw, all other screws are locking head screws to maintain the reduction.
- **f** AP x-ray after uneventful healing 1 year after the operation.

tool. Or the reduction can be maintained by reducing the joint block against the shaft with the help of the large femoral distractor, the external fixator, or by percutaneous clamping using a collinear clamp or a cerclage wire (**Fig 3.1.3-11**) before insertion and fixation of the plate.

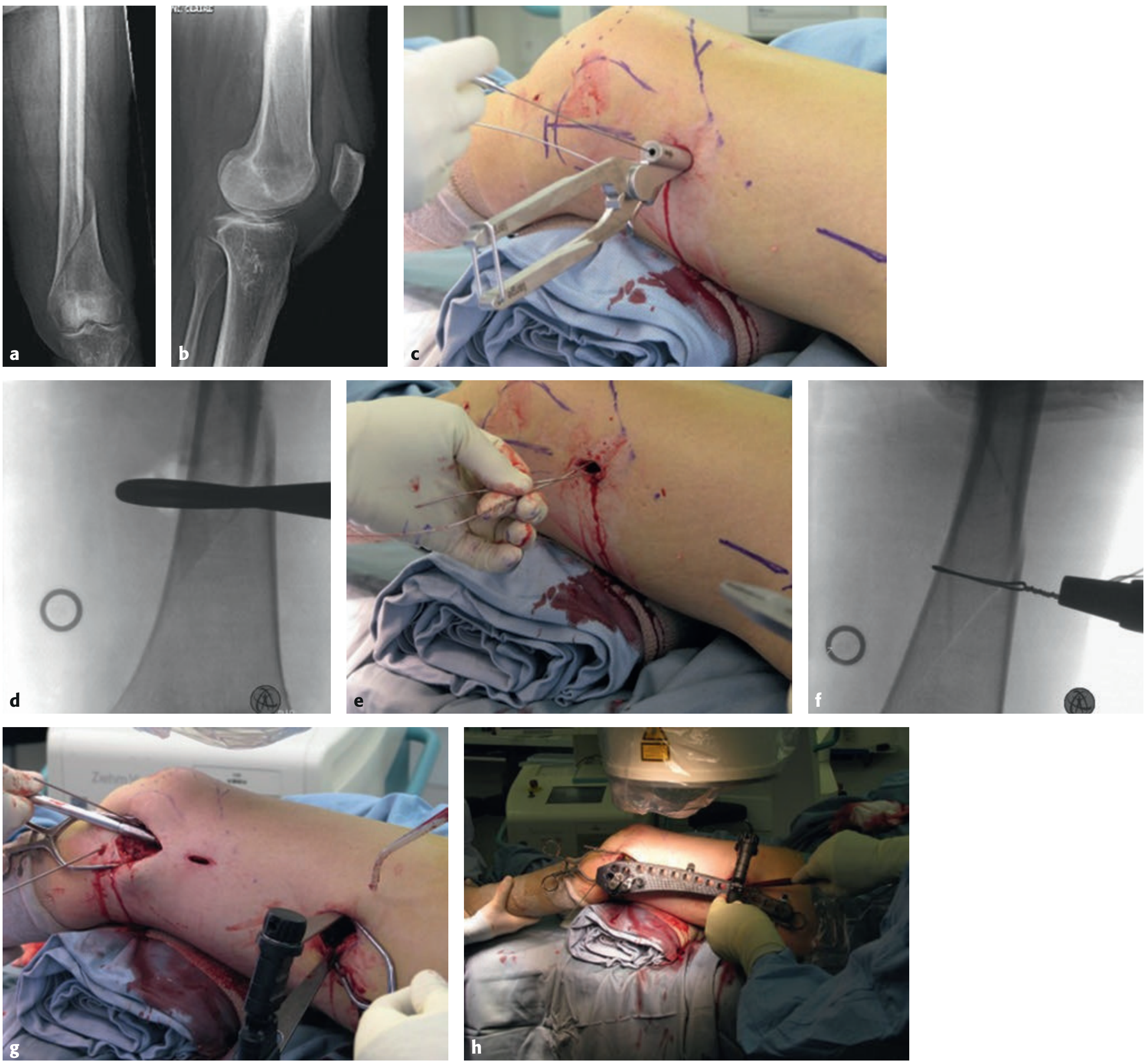


Fig. 3.1.3-11a–l

a–b A 56-year-old woman with an extraarticular spiral distal femoral fracture.

c Direct reduction of the spiral fracture with minimally invasive plate osteosynthesis (MIPO) wire passer (**Fig 3.1.1-17**).

d Intraoperative C-arm picture with wire passer in situ.

e After extraction of the wire passer instrument, the cerclage wires were ready to be tightened.

f Maintaining reduction of the shaft facture with the cerclage.

g Submuscular insertion of the MIPO epiperiosteal surfer tunneling instrument.

h Insertion and fixation of the less invasive stabilization system distal femur using the aiming arm.

Patient selection: All distal femoral fractures (33A and 33C) are suitable for MIO with distal femoral nails or MIPO. Complex 33C fractures are more reliably treated with LCP-DF after the articular surface is addressed.

5.4 Tibia

5.4.1 Tibia proximal

Principle: Proximal tibial fractures caused by high-energy trauma, with or without dislocation are challenging fractures to treat because the soft-tissue envelope around the knee joint is often severely injured. After the first assessment, the treatment in most of these fractures is the application of a spanning external fixator followed by computed tomographic (CT) (span and scan). The pins of the external fixator should be outside the zone of injury and potential implant position. According to the fracture pattern, two different fixation strategies are applied. In extraarticular (41A) and partial articular (41B) fractures, single column plating is sufficient. In bicondylar intraarticular fractures (41C), the application of single or double column plates depends upon the fracture pattern. In bicondylar fractures, a posteromedial approach buttressing the medial column is performed as a first step. The second step addresses the intraarticular fracture, before definitive fixation between the joint and the shaft takes place on the lateral side (to combine the articular block with the shaft). If there is a simple cortical fracture in the medial column, which can be reduced anatomically to a stable position, then lateral column fixation alone, using an LCP, may be sufficient. Different medial and posteromedial anatomical plates are available but conventional tubular plates 3.5 or LCPs 3.5 may be sufficient if buttress fixation alone provides stability. Depending upon the extension of the fracture into the proximal shaft, anatomical plates 3.5 or 4.5/5.0 (proximal tibial LCP) allow for safe stabilization (**Fig 3.1.3-12**).

Patient selection: High-energy proximal tibia fractures or low-energy fractures with soft tissue compromise profit from a soft tissue friendly MIPO approach (41A, 41B, 41C). In open fractures, the soft-tissue envelope should be reestablished after thorough debridement together with the MIPO technique or the osteosynthesis should be performed in a staged procedure after definitive soft-tissue cover [23].

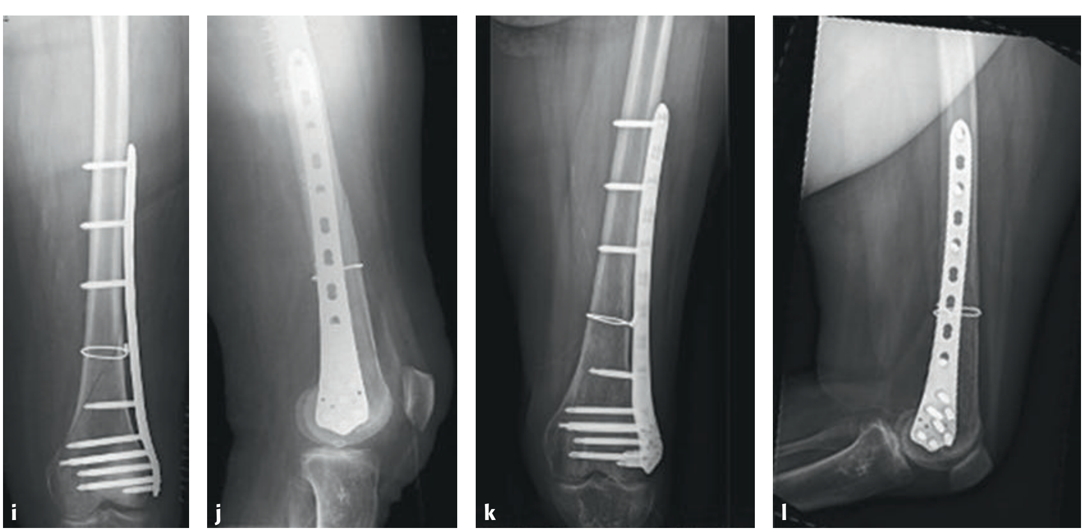


Fig. 3.1.3-11a–l (cont)
i–j AP and lateral view of postoperative x-ray.
k–l X-ray control after 2 years.

Fig. 3.1.3-12a–h

a–c A 49-year-old patient with a closed bicondylar 41C3 tibial plateau fracture.

d After initial joint spanning external fixator and compartment release. The compartment release was closed before minimally invasive plate osteosynthesis fixation took place.

e Before a locking compression plate proximal tibia (LCP-PT) was inserted, the lateral plateau was reduced and additionally buttressed with rafting screws through a tubular plate 2.7.

f–g Postoperative AP and lateral x-rays with reduction plate on the medial side and AP reduction screws. Lateral buttressing of the lateral column with an LCP-PT and tubular raft plate 2.7 proximally.

h One year after surgery, fracture healing with good alignment.

5.4.2 Tibia shaft

Principle: MIPO for tibia midshaft fractures is the exception. Intramedullary nailing is the gold standard for the treatment of this bone segment. Straight DCP, LC-DCP, or LCP plates 5.0/4.5 are used for MIPO. Long plates with 12–16 holes are needed in multifragmentary fractures, extending proximal or distal. In this situation, additional bending to fit the proximal or distal flare is needed. Correct bending and twisting are of importance to keep correct alignment and rotation of the tibia to avoid reduction loss when using conventional screws. Plate position is chosen according to the fracture pattern, the soft-tissue condition, and at the discretion of the surgeon. Medial plating is easier but may cause hardware prominence leading to wound breakdown. This is more common in slim patients (with little subcutaneous fat) and in elderly patients with frail skin and impaired circulation. Plate insertion starts either proximal or distal through a soft-tissue window of 3–4 cm, close to the posteromedial border of the tibia. At the proximal metaphysis a transverse incision is often easier to use. Distally, the greater saphenous vein and the nerve have to be avoided. Reduction with the help of the plate (**Fig 3.1.3-13**) or preliminary reduction in simple fractures using percutaneous clamps or an external fixator before inserting the plate are the two strategies used. The contralateral leg, if draped free may serve as a template for length, alignment, and rotation. If a lateral plate position is chosen, soft-tissue cover is much better but plate application is more difficult and contouring the plate is more difficult as a twist is required. In the distal tibia, the soft-tissue window has to be large enough to avoid harm to the anterior tibia vessels and the deep peroneal nerve.

Patient selection: MIPO is only indicated for closed and first and second degree open tibial midshaft fractures if nailing is not possible due to:

- Fracture extension into the articular surface of the tibia
- Proximal and distal shaft fractures
- Some segmental fractures
- A small medullary canal
- A medullary canal blocked by an implant
- A periprosthetic fracture
- A deformed medullary canal
- Open growth plates

Fig. 3.1.3-13a–k

a–b A 51-year-old patient with a spiral fracture of the distal diaphysis (42A1). With fracture line extending into the tibial plafond.

c Medial percutaneous plate insertion.

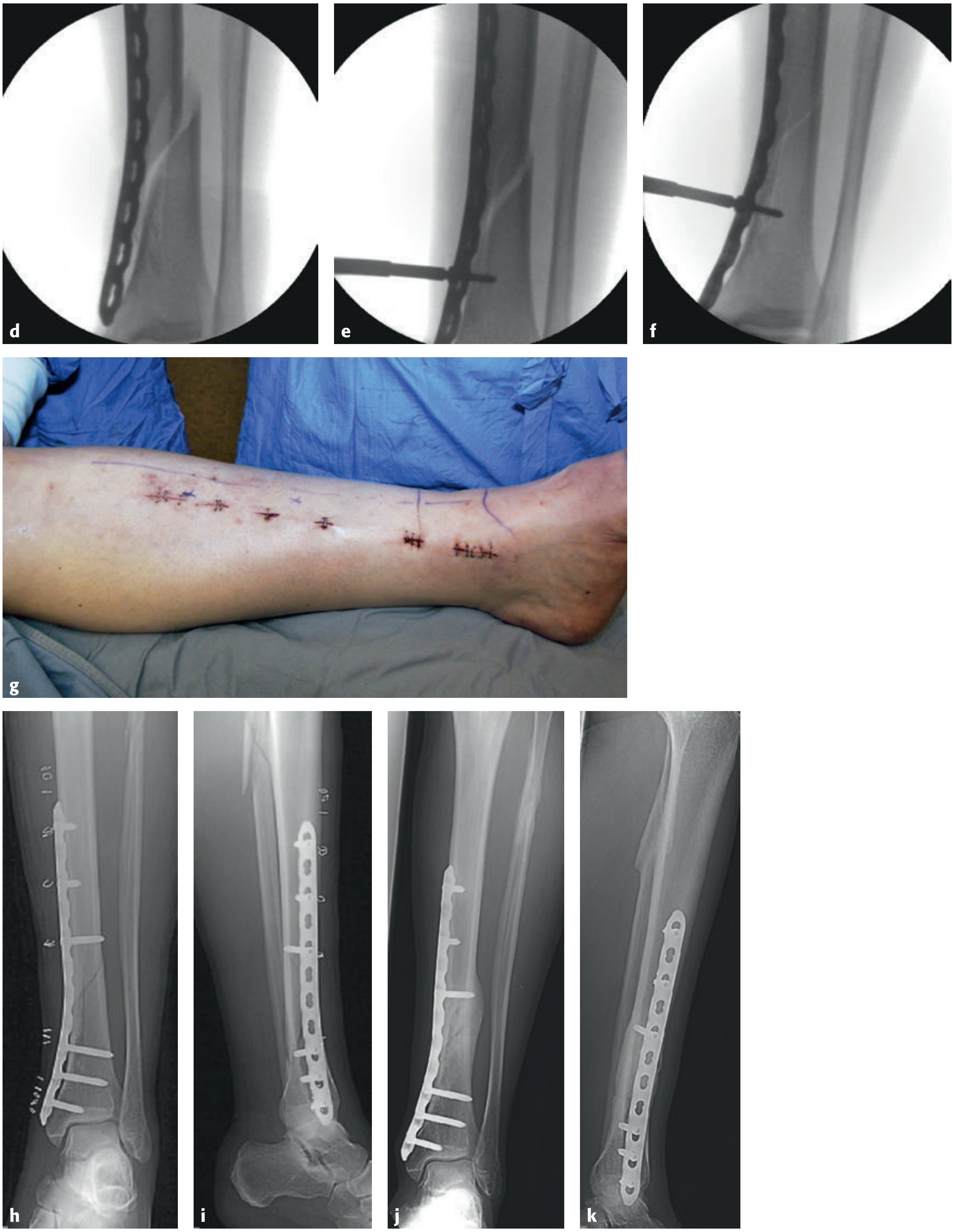


Fig. 3.1.3-13a–k (cont)

d Under traction, the displaced distal fragment was not aligned with the precontoured plate.

e Percutaneous insertion of a cortical screw as a reduction screw.

f After tightening the screw, the distal fragment was reduced against the plate.

g Closed skin incisions of the distal tibia.

h–i Postoperative AP and lateral x-ray. Note after proximal and distal fixation with locking head screw, the reduction screw was replaced by a LHS.

j–k AP and lateral view 1 year after fixation. Note the callus after applying bridge plate fixation.

5.4.3 Tibia distal intraarticular

Principle: In distal tibial fractures involving the joint and/or the metaphysis, the condition of the soft tissue plays a key role when considering MIPO procedures. Displaced fracture fragments should be reduced and the tibia aligned by immobilization in a well-padded splint or in an external fixator before CT scans (span and scan). In low-velocity injuries with extraarticular fractures that are not amenable to nailing, MIPO is a reliable and safe approach for all fracture patterns, especially C-type fractures [24]. Depending on the fracture pattern and the soft-tissue condition, a staged procedure is recommended, especially in high-velocity injuries. After swelling has subsided, the articular fracture is addressed from anteromedial (**Fig 3.1.3-14**), anterior, anterolateral, posterolateral or posteromedial or combinations of these approaches depending upon the fracture pattern. Incisions must be large enough to achieve an anatomical reduction of the joint and bone graft or substitute should be used to support the articular surface. Visualization and reduction of the joint is facilitated by using the large femoral distractor. According to the fracture pattern, plates are inserted from distal to proximal without stripping the periosteum and plate fixation on the shaft is achieved by percutaneous screw fixation.

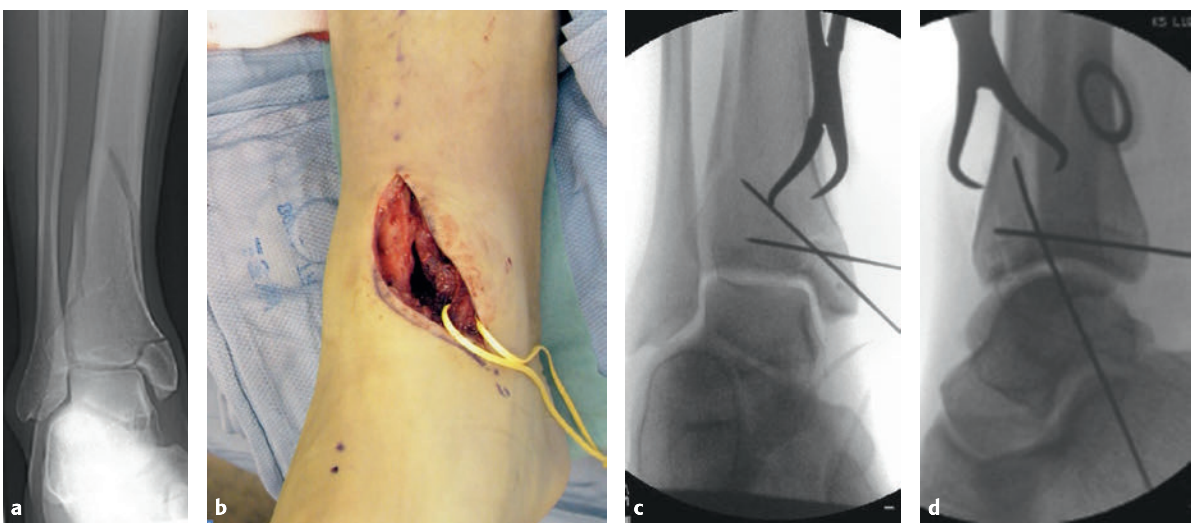


Fig 3.1.3-14a–l
- **a** A 21-year-old patient with a rotational pilon fracture.
- **b** Skin incision at the level of the ankle joint. The greater saphenous vein was tagged.
- **c–d** Open reduction and internal fixation (ORIF) of the articular fractures, initially with temporary K-wires.
- **e–f** Definitive fixation of the articular surface with three lag screws.

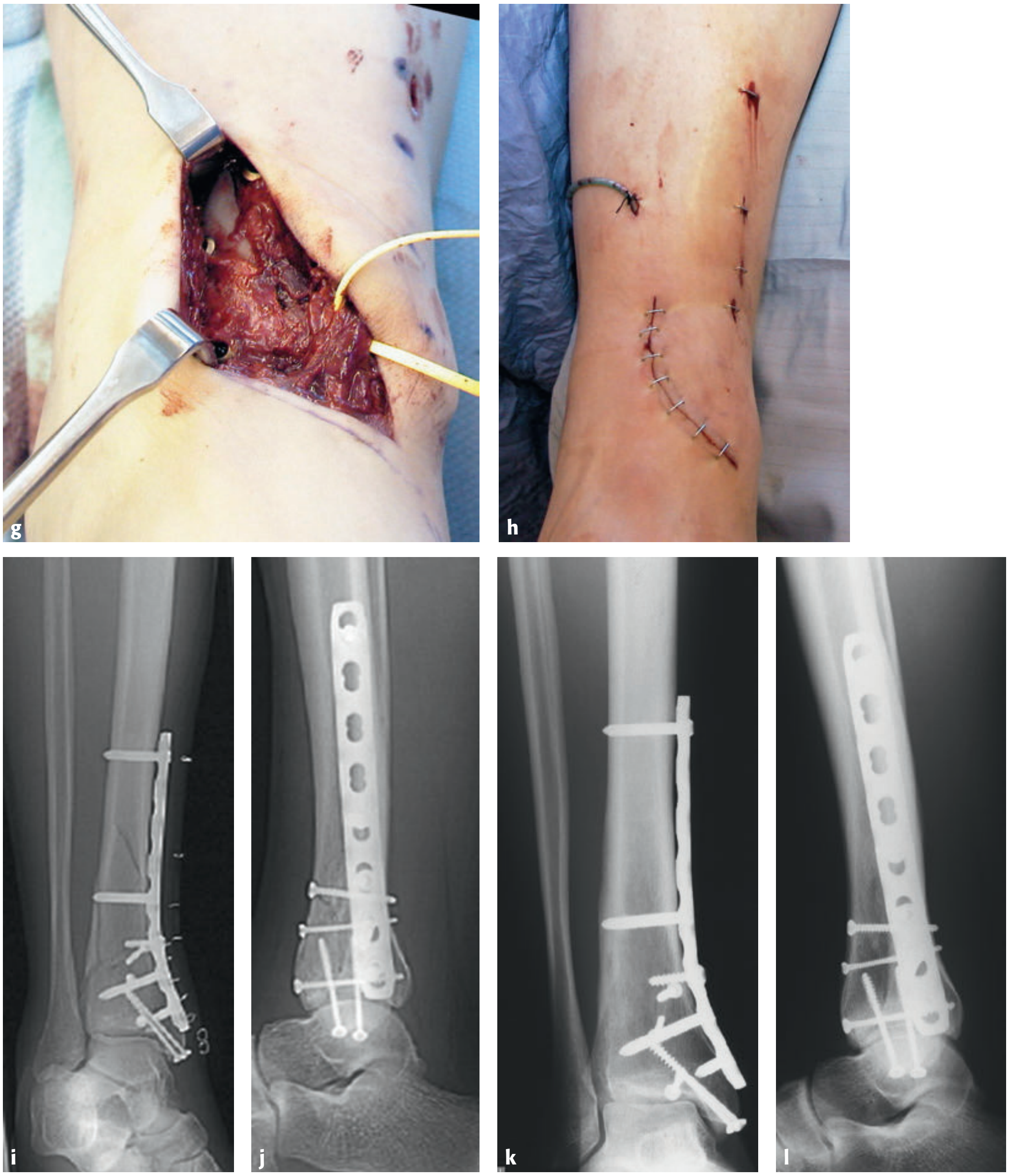


Fig 3.1.3-14a–l (**cont**)
g Distal tibia after open reduction internal fixation of the articular block and plate insertion.
h Stapled skin incision.
i–j Postoperative x-rays.
k–l AP and lateral view 1 year after the operation. The fracture healed with no signs of ankle arthrosis.

Patient selection: Extraarticular fractures (43A) which are not amenable to new antegrade nail designs are good indications for MIPO, as well as tibia plafond fractures with fracture extensions into the shaft. Simple fracture patterns (43A1, 43A2, and 43A3) require anatomical reduction and fixation with absolute stability while bridge-plate fixation and relative stability is used for multifragmentary fractures (43B and 43C). Several anatomical low profile plates are available (anterolateral tibial plate 3.5, LCP 3.5, metaphyseal plate 3.5/2.7, distal tibial T-plate 3.5/4.5/5.0, 3.5) to treat these fractures by buttressing the joint block from the anterolateral, posterior, or anteromedial sides. The requirement and sequence of fibular fixation depends on its fracture pattern and the fracture pattern of the distal tibia. Anatomical reduction of the fibula helps in most situations to achieve correct length and position of the attached posterolateral tibia plafond and adds to the stability. The mortise must always be checked for stability once alignment is assured.

6 Complications

The principle of minimally invasive surgery is to reduce operative trauma from surgical approaches and at the fracture site.

Short skin incisions are not the goal of MIO surgery, as they may result in significant traction to the underlying soft tissue and the skin.

This may provoke soft-tissue necrosis and secondary infection. Apart from gentle soft-tissue handling, MIO/MIPO surgery requires meticulous preoperative planning and correct positioning of the patient and image intensifier to allow for indirect reduction techniques.

Skin break down

Skin breakdown, with or without infection, may occur when too much tension has been applied to the soft tissue with retractors or with sutures. It may also be caused by prominent plates causing pressure necrosis. This can be a particular problem in some sites, such as the medial border of the tibia, if locking screws alone are used as these allow the plate to stand proud of the bone.

Deep infection

Compared with conventional open procedures, infection rates after MIO have been reported to be lower, even in cases of open fractures [4]. But disproportionate traction on skin and soft tissue as well as repetitive insertion and removal of the plate may cause a deep infection. Minimally invasive surgery is not necessarily minimal infection surgery.

Malunion

Indirect reductions of the fracture site and the reduced diameter of the C-arm image are inherent risks for creating a malunion. Intraoperative assessment of length, alignment, and rotation under stable conditions is important. Maintenance of the achieved reduction with adjuncts like the inserted and temporarily fixed plate, an external fixator, a large femoral distractor or a traction table are as important as using the contralateral uninjured leg as a template in the lower extremity.

The learning curve for MIPO procedures is steep and elevated rates of malunion are reported for MIPO surgery [7, 12]. Locking plates and anatomically preshaped plates have decreased the learning curve. However, the surgeon cannot solely rely upon precontoured plates for reduction because there is variation in normal anatomy.

Delayed union/nonunion

Nonunion is uncommon following MIPO, provided the principles of internal fixation are followed. In high-velocity fractures, the necessity for secondary bone graft is between 2.5% and 7% [12, 22, 23]. Secondary bone grafting is advised when no callus formation is visible after 6–8 weeks. Simple fractures, when treated with a bridge plate, are at risk of delayed healing because gap-healing is required and fatigue failure of the plate may occur before the fracture heals. Anatomical reduction and fracture fixation with absolute stability using compression is recommended for simple (type A) fracture patterns.

Implant failure

Plate breakage after MIPO has been observed in cases of delayed union. This may be due to distraction with a fracture gap > 2 mm, high-energy impact with soft-tissue injury and devascularization of the bone fragments or failure to achieve absolute stability in a simple fracture pattern. Screw placement too close to a fracture gap when providing a bridge plate concept will also lead to implant failure, as lack of relative stability will prevent callus formation: gap healing is slow in this situation of "too much stability" with subsequent fatigue failure of the implant (**Fig/Animation 3.1.3-15**). When using locking screws the plate has to be placed on the center of the shaft to obtain enough screw purchase to achieve the planned stability of the implant (**Fig 3.1.3-16**).

7 Implant removal

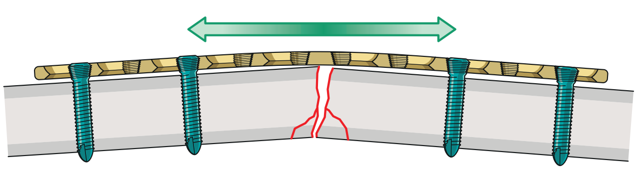
Implant removal after MIO may be more difficult than implant insertion. As swelling subsides, incisions are often not in their original position relative to a screw. Patients should be warned that a larger incision may be needed to remove the implants. Special instruments and drill bits should be available when performing implant removal. This may facilitate hardware removal, especially when LHS are jammed in the plate because of poor insertion technique or bone ingrowth onto titanium implants [9].

8 Education in MIO and how to start

Minimally invasive plate osteosynthesis surgery is a form of minimal access osteosynthesis. Minimal invasiveness is not defined by the lengths of the incision but more by the reduction technique under the conditions of limited visual control. This technique is more demanding. The principles of internal fixation using plates and the application of other MIO procedures, such as external fixators and intramedullary nailing, should be well known to the surgeon. Minimally invasive plate osteosynthesis should not be performed by inexperienced trauma surgeons. Open procedures should be the first step for the learning surgeon who then can proceed to more difficult MIPO cases as they arise.

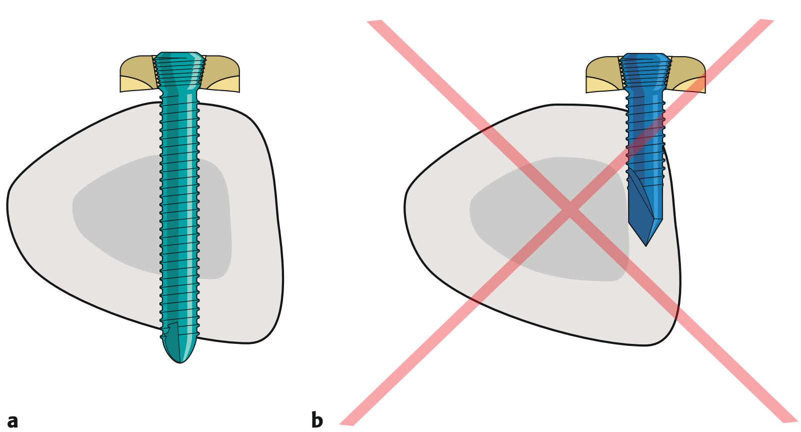
9 Conclusion

Technology for fracture fixation has rapidly evolved in recent years. Specific instruments for percutaneous fracture reduction and numerous plates for many anatomical regions with locking head screws have facilitated MIPO surgery. The soft-tissue preserving goal of this surgery is appealing and has helped spread this novel technique. However, this technique is demanding and needs a step-by-step approach with critical case analysis, proper preoperative planning, creation of a stable operative field, and C-arm visualization of the achieved reduction before definitive fixation. The biomechanical principles of plate osteosynthesis are identical and should not be compromised using this technique. The goals of surgery remain the same.



a b

Fig/Animation 3.1.3-15a–b Stress distribution. Influence of screw fixation on forces within the plate.



a b

Fig 3.1.3-16a–b Plate position has to be centered on the shaft to avoid tangential screw placement, which is associated with loss of fixation.

Classic references | Review references

10 References

1. **Mast J, Jakob R, Ganz R.** *Planning and Reduction Technique in Fracture Surgery*. 1st ed. Berlin Heidelberg: Springer Verlag; 1989.
2. **Krettek C, Schandelmaier P, Tscherne H.** [Distal femoral fractures. Transarticular reconstruction, percutaneous plate osteosynthesis and retrograde nailing.] *Unfallchirurg*. 1996 Jan;99(1):2–10. German.
3. **Frigg R.** Development of the locking compression plate. *Injury.* 2003 Nov;34 Suppl 2:B6–10.
4. **Babst R, Bavonratanavech S, Pesantez R.** *Minimally Invasive Plate Osteosynthesis (MIPO). 2nd ed.* Stuttgart: Thieme Verlag; 2012.
5. **Babst R, Hehli M, Regazzoni P.** [LISS tractor. Combination of the "less invasive stabilization system" (LISS) with the AO distractor for distal femur and proximal tibial fractures.] *Unfallchirurg*. 2001 Jun;104(6):530–535. German.
6. **Perren SM, Fernandez dell'Orca F, Regazzoni P et al.** New aspects of cerclage: improved technology applicable to MIO with special reference to periprosthetic fractures. In: *Minimally Invasive Plate Osteosynthesis.* 2nd ed. Stuttgart: Thieme Verlag; 2012.
7. **Buckley R, Mohanty K, Malish D et al.** Lower limb malrotation following MIPO technique of distal femoral and proximal tibial fractures. *Injury.* 2011 Feb;42(2):194–199.
8. **Gautier E, Sommer C.** Guidelines for the clinical application of the LCP. *Injury.* 2003;34 Suppl 2:63–76.
9. **Georgiadis GM, Gove NK, Smith AD, et al.** Removal of the less invasive stabilization system. *J Orthop Trauma.* 2004 Sep;18(8):562–564.
10. **Hasenboeler E, Rikli D, Babst R.** Locking compression plate with minimally invasive plate osteosynthesis in diaphyseal and distal tibial fractures: a retrospective study of 32 patients. *Injury.* 2007 Mar;38(3):365–370.
11. **Livani B, Belangero WD.** Bridging plate osteosynthesis of humeral shaft fractures. *Injury.* 2004 Jun;35(6):587–595.
12. **Zlowodzki M, Bhandari M, Marek DJ, et al.** Operative treatment of acute distal femur fractures: systematic review of 2 comparative techniques and 45 case series (1989 to 2005). *J Orthop Trauma.* 2006 May;20(5):366–371.
13. **Livani B, Belangero WD, Castro De Medeiros R.** Fractures of the distal third of the humerus with palsy of the radial nerve: management using minimally invasive percutaneous plate osteosynthesis. *J Bone Joint Surg Br.* 2006 Dec;88(12):1625–1628.
14. **Gauger EM, Cole PA.** Surgical technique: a minimally invasive approach to scapula neck and body fractures. *Clin Orthop Relat Res.* 2011;469(12):3390–3399.
15. **Routt ML Jr, Nork SE, Mills WJ.** Percutaneous fixation of pelvic ring disruptions. *Clin Orthop Relat Res.* 2000 Jun;(375):15–29.
16. **Rammelt S, Amlang M, Barthel A, et al.** Percutaneous treatment of less severe intraarticular calcaneal fractures. *Clin Orthop Relat Res.* 2010 Apr;468(4):983–990.
17. **Oh CW, Song HR, Kim JW, et al.** Deformity correction with submuscular plating technique in children. *J Pediatric Orthop B.* 2010 Jan;19(1): 47–54.
18. **Oh CW, Song HR, Kim JW.** Limb lengthening with a submuscular locking plate. *J Bone Joint Surg Br.* 2009 Oct;91(10):1394–1399.
19. **Sohn HS, Kim WJ, Shon MS.** Comparison between open plating versus minimally invasive plate osteosynthesis for acute displaced clavicular shaft fractures. *Injury.* 2015 Aug;46(8):1577–1584.
20. **Lin T, Xiao B, Ma X, et al.** Minimally invasive plate osteosynthesis with a locking compression plate is superior to open reduction and internal fixation in the management of the proximal humerus fractures. *BMC Musculoskelet Disord.* 2014;15:206:1–7.
21. **Kim JW, Oh CW, Byun YS, et al.** A prospective randomized study of operative treatment for noncomminuted humeral shaft fractures: conventional open plating versus minimal invasive plate osteosynthesis. *J Orthop Trauma;* 2015 Apr;29(4):189–194.
22. **Oh CW, Kim JJ, Byun YS, et al.** Minimally invasive plate osteosynthesis of subtrochanteric femur fractures with a locking plate: a prospective series of 20 fractures. *Arch Orthop Trauma Surg.* 2009 Dec;129(12):1659–1665.
23. **Kim JW, Oh CW, Jung WJ, et al.** Minimally invasive plate osteosynthesis for open fractures of the proximal tibia. *Clin Orthop Surg.* 2012 Dec;4(4):313–320.
24. **Zou J, Zhang W, Zhang CQ.** Comparison of minimally invasive percutaneous plate osteosynthesis with open reduction and internal fixation for treatment of extra-articular distal tibia fractures. *Injury.* 2013 Aug;44(8):1102–1106.

11 Acknowledgments

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3.2.1 Screws

Wa’el Taha

1 Design and function

1.1 What is a screw?

A screw is a powerful mechanical device that converts rotation into linear motion.

Most screws used for fracture fixation share several design features (**Fig 3.2.1-1**):

- Central core that provides strength
- Thread that engages the bone and converts rotation into linear motion
- Tip that may be blunt or sharp
- Head that engages either the bone or the plate
- Recess to attach a screwdriver

Screws come in different shapes and sizes and their names are based upon a number of factors (**Fig 3.2.1-2**):

- Design (eg, cannulated, locking head)
- Dimension (eg, 4.5 mm)
- Characteristics (eg, self-tapping, self-drilling)
- Area of application (cortex, cancellous, monocortical, or bicortical)
- Function or mechanism

Since the introduction of locking head screws (LHS), all other types of screws are referred to as “conventional” screws. A screw can be applied to compress a fracture surface (lag screw), fix a plate to the bone by producing compression between the plate and the bone (plate screw), or it may be used to fix an external fixator (Schanz screw) or internal fixator (locking head screw) to the bone. A position screw holds two fragments together without compression. Lag screws can be inserted through a plate or independently. The term lag screw does not describe screw design but refers to the function of compressing two fragments together.

Rotation of a screw is converted in to linear motion by screw threads. As the screw advances, the head is pressed against the bone cortex and further advancement of the screw compresses the head against the cortex, creating a preload. This preload compresses the fracture and prevents separation, while friction between the fracture surfaces and between the screw and the bone opposes displacement by shear. Lag screws are used to achieve absolute stability. In contrast, LHS have a head with a thread that matches a reciprocal thread in the hole of the plate (**Fig/Animation 3.2.1-3**). As it advances, it forms a mechanical couple with the plate that does not rely on compression between the two elements. This produces angular stability and the plate is not pressed against the bone. The load transfer of this construction occurs via the plate, not by preload and friction. This is the same principle as that of an external fixator and the stabilizing effect of LHS and Schanz screws is based on their bending stiffness plus the mechanical couple to the plate or the external fixator frame.

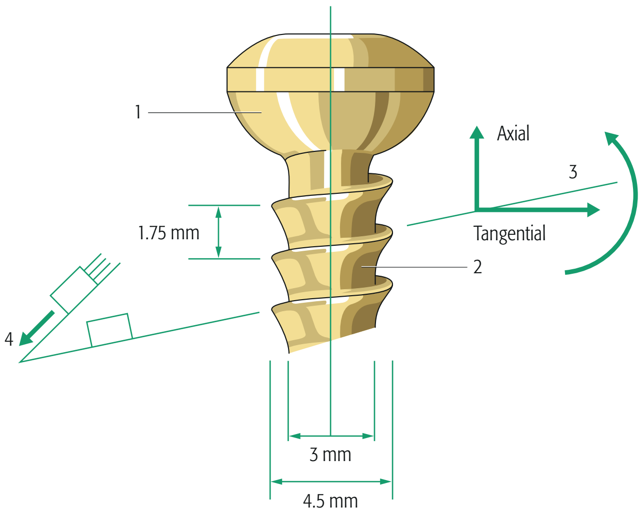


Fig 3.2.1-1 A conventional cortex screw, as used in diaphyseal bone. The underside (1) of the screw head is spherical, allowing a congruous fit to be maintained while tilting the screw, eg, within a plate hole. The thread (2) is asymmetrical with the pitch of 1.75 mm. The dimensions shown are designed to offer a good relation between axial forces and torque applied (3), and these dimensions result in an inclination of the thread which is self-locking (4). The screw corresponds to the ISO standard 5835. In this example of a screw, 3 mm demonstrates the "core" diameter of the screw and 4.5 mm demonstrates the "thread" diameter of the screw.

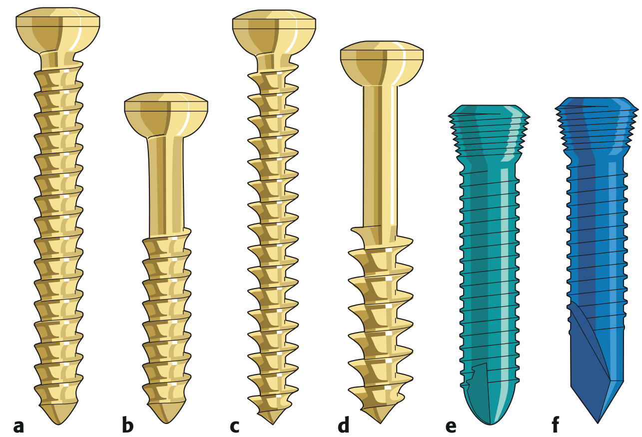
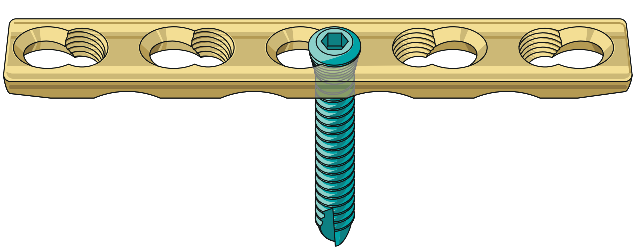


Fig 3.2.1-2a–f The types and functions of screws differ, however all screws have a head that has a recess for the screwdriver attachments. The core diameter of the screw corresponds to the size of the drill bit used to create a tract for the screw. The thread diameter of the screw corresponds to the screw size, ie, 3.5 mm or 4.5 mm. The tip of the screw can be rounded or pointed depending upon whether it is self-tapping or non self-tapping in function. The pitch (distance between the thread) of the screw differs according to the screw being cortical or cancellous or locking in nature.

- **a** Cortex screw.
- **b** Partially threaded cortex screw.
- **c** Cancellous bone screw.
- **d** Partially threaded cancellous bone screw.
- **e** Locking head screw.
- **f** Self-tapping/self-drilling locking head screw.



Fig/Animation 3.2.1-3 The threaded screw head locks within the reciprocal threads of the locking compression plate (LCP). The combination hole allows for insertion of a conventional screw as an alternative.

A screw is an efficient tool for the fixation of a fracture by interfragmentary compression or for fixing a splint, such as a plate, intramedullary nail or fixator, to the bone.

1.2 Biomechanics

The axial force produced by a screw (**Fig 3.2.1-4a**) results from rotating it clockwise, whereby the inclined surface of its thread glides along a corresponding surface of the bone. The inclination of the thread—the pitch—must be small enough to provide purchase of the screw in bone, ie, to prevent the screw from unwinding and becoming loose (**Fig 3.2.1-1**) and the pitch must be large enough to allow full insertion with an acceptably low number of revolutions [1].

Turning the screw within bone creates friction, which in turn generates heat. Screw design and the method of insertion will have a major influence on the amount of heat generated. This heat has the potential to cause thermal necrosis of bone with subsequent loosening of the screw and must be avoided. Thermal necrosis can also be caused by blunt drill bits or by inserting large diameter (> 2 mm) wires and pins into cortical bone without appropriate predrilling. It is the surgeon's responsibility to avoid this.

Two forces are active, one along the circumference of the screw thread (tangential), the other along the axis of the screw (axial). The first results from the torque of insertion. The second results from the displacement along the inclined surface between screw thread and bone thread, which produces axial tension. At the same time, the axial force acting upon the inclined surface produces torque, which tries to unwind the screw. This force increases with the inclination. As the friction remains constant, the range of angle of inclination that can be used is limited.

The torque applied to a conventional 4.5 mm cortex screw during tightening is divided into three components:

- 50% is used to overcome friction at the screw head interface
- 40% is transformed into axial force
- 10% overcomes the friction of the thread

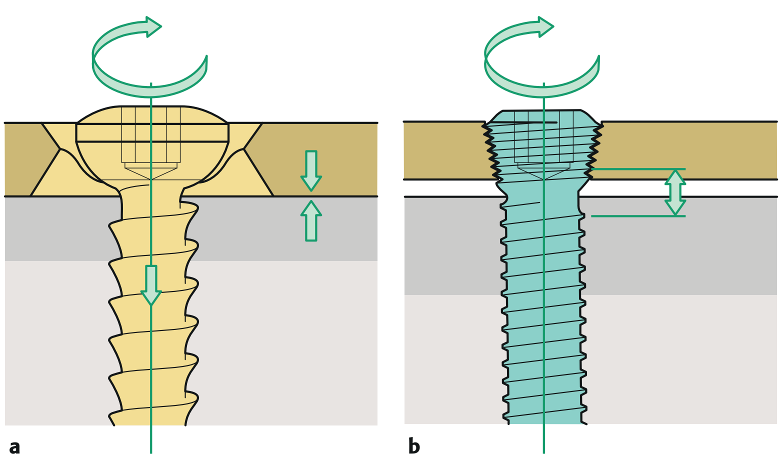


Fig 3.2.1-4a–b Conventional and locking head screws.

a This shows the design and force components of a conventional screw as used for the dynamic compression plate (DCP) and limited-contact DCP (LC-DCP). The screw acts by producing friction between the underside of the plate and the bone surface due to compression of the interface.

b Locking head screws as used in the less invasive stabilization system (LISS) and locking compression plate (LCP). They work more like bolts than screws; the axial force produced by the screw is minimal. The screw provides fixation based on the fact that the screw head is locked in a position perpendicular to the body of the plate that is not pressed against the bone. Such systems act like fixators rather than as plates.

Thus, during bench testing, a screw inserted through a plate hole can be tightened to nearly twice the torque that an isolated screw can. The reason for this is that the cortex under the head of an isolated screw is more likely to fail because of concentrating the force from the screw head to a small contact area on the bone. In cortical bone, the countersink can be used to increase the area of contact between the head of the screw and the cortex. This reduces contact stress and the risk of local microfracture beneath the screw head, especially if the screw is inclined (**Fig 3.2.1-5**). The relation between torque applied and axial force induced is about 670 N/Nm for a conventional 4.5 mm cortex screw. In LHS, once the screw head engages within the plate hole, practically all torque is used for locking, and the torque applied to the screw thread is minimal. The screw thread is, therefore, protected, as it will only withstand functional forces without preload. This explains the observation that in a closely monitored clinical series of more than 2,000 inserted titanium LHS not one failure occurred [1]. However, if a surgeon applies uncontrolled torque during tightening, something will have to give way. This could be the connection to the drive where, at higher torque, the hexagonal recess may strip, especially if a worn-out screwdriver is used.

It is important that the surgeon checks the quality of the screwdriver tip regularly before use.

The compression applied by a screw affects a comparatively small area of the surrounding bone. Therefore, a single screw compressing an oblique fracture does not effectively counteract rotation of the bone fragments around the axis of that screw. The area of the compression induced around the screw is small. This is of importance with respect to torque acting upon smooth osteotomy surfaces: a single screw applied to a surface does not provide much resistance against torque between the two fragments. Such situations require a second screw placed well apart from the first one and, if possible, in a different direction. The leverage then corresponds to the distance between the screws plus twice the leverage of the single screw (**Fig 3.2.1-6**).

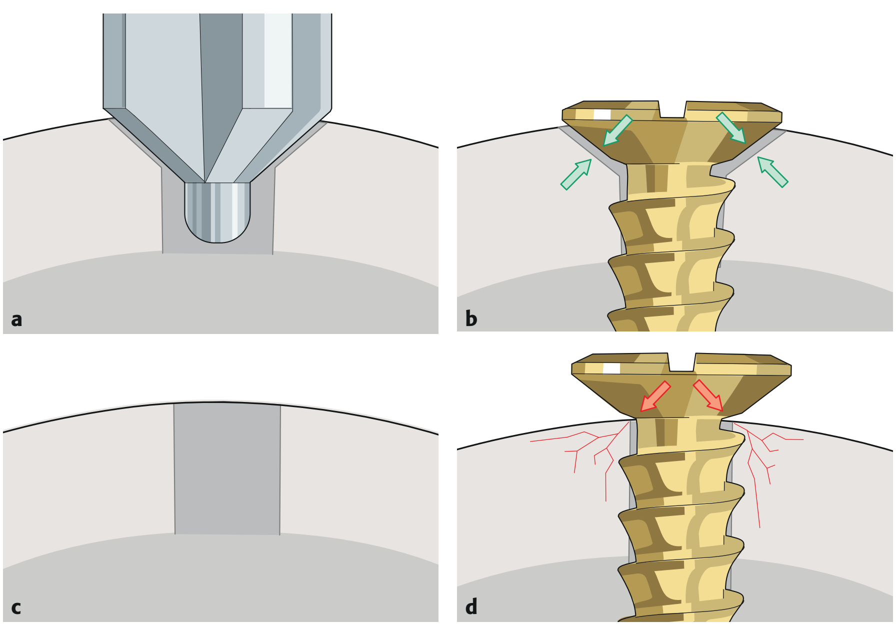


Fig 3.2.1-5a–d The countersink device is used to prepare the bone to receive the head of the screw so that the contact area between the screw head and the bone is increased (**a–b**). Without countersinking, forces would concentrate at a small area (**c–d**).

1.3 Screw thread

There are three types of screw threads used for the AO technique:

- The cortex screw thread is designed for application in diaphyseal bone and is available in different sizes.
- The cancellous bone screws have a deeper thread, a larger pitch, and a larger outer diameter than the cortex screws. Their applications are in metaphyseal or epiphyseal cancellous bone.
- The LHS used with the locking compression plate (LCP) (**Fig 3.2.1-4b**) are characterized by a larger core diameter and a comparatively shallow thread with blunt edges. These result in increased strength and a larger interface between screw and bone compared with conventional screws [2]. The head of the screw is also threaded. The shallow profile of the thread demands precise insertion technique with the power drive to prevent toggling that will result in a reduction of purchase at the screw thread – bone interface [3]. The advantages and hazards of the LHS are described in detail in chapters 3.3.2 and 3.3.4.

When inserting LHS, the last revolutions must always be done by hand using a torque-limiting screwdriver.

1.4 Screw tip

Different designs are available for the tip of the screw, and these include:

- Smooth, conical tips for insertion into a tapped drill hole
- Self-tapping, which will cut a channel for the thread
- Self-tapping/self-drilling, which will cut a drill hole and channel for the thread

A tap is an instrument that cuts a channel for the thread of a screw. The original, smooth, conical-tipped screws were designed for insertion after the drill hole had been tapped. Tapping may reduce the pull-out strength of screws because inadvertent toggling of the tap causes the hole to be enlarged to a size greater than actually needed. In osteoporotic and cancellous bone it is often better to avoid using a tap or to use a tap for just the near cortex to allow engagement of the screw. Tapping using the power drive reduces toggle but deep penetration can be more difficult to control and is dangerous.

In dense cortical bone the flutes of the screw may clog and a tap must be used. In this situation, it is important that the tap is reversed one half turn for every three or four complete

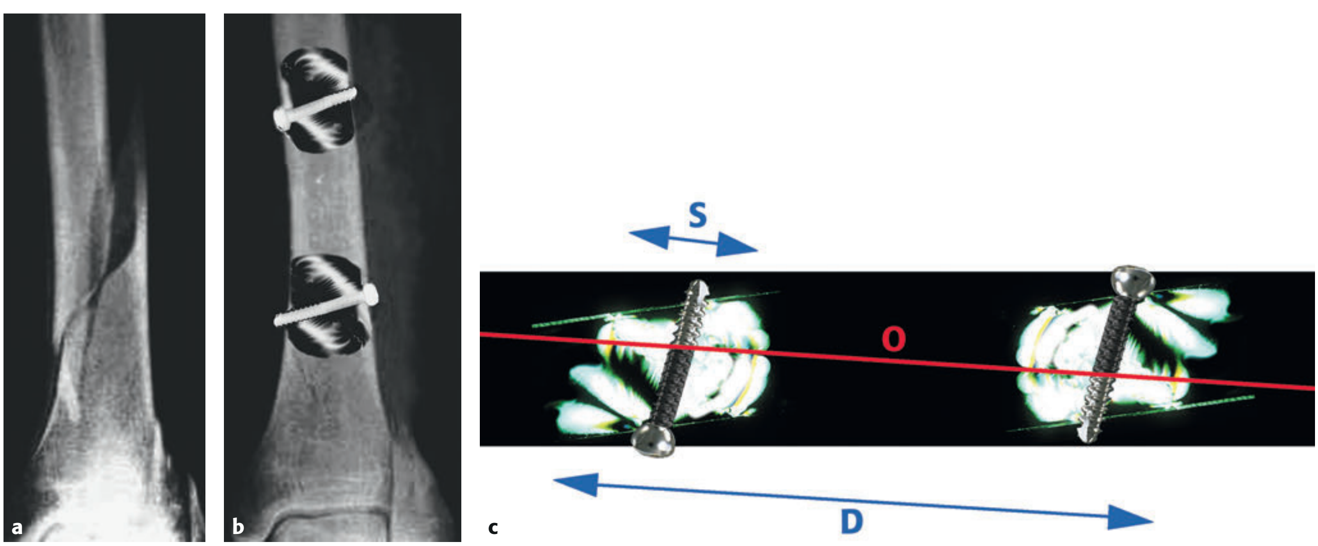


Fig 3.2.1-6a–c The different effects of using one or two lag screws for stabilization against torque in pure lag screw fixation.

a Model of a spiral fracture in a diaphysis.

b Fixation of the fracture using two lag screws. The extent of interfragmentary compression around a lag screw is demonstrated by a photoelastic experiment. The photoelastic pictures are superimposed on the x-ray to give a rough idea of the distribution of compression.

c In this figure the area of compression around a lag screw, as obtained from a photoelastic experiment, has been inserted into a schematic drawing of a long oblique osteotomy to explain the different effect of one lag screw alone (S) compared with the effect of two well-spaced lag screws (D).

S Lever arm of a single lag screw.
D Lever arm of double lag screws.
O Osteotomy.

This schematic diagram shows that whenever lag screws are used alone, there should be at least two well-spaced screws.

turns forward. This clears bone debris into the channel in the tap to reduce friction and prevent jamming that may result in the tap breaking.

Self-tapping screws have several advantages, including ease and speed of application [4]. However, it is still necessary to use a tap in hard cortical bone in young adults. This is particularly important for the smaller screw sizes (3.5 and 2.7 mm) as the screw heads may break if high torque is used to insert the screw without tapping.

Self-tapping screws must be accurately inserted without toggling and may be difficult to use during minimally invasive plate osteosynthesis techniques as soft-tissue tension may cause misdirection of the screw. The cutting flutes reduce the amount of contact between screw and the bony cortex. This may reduce the pull-out strength of the screw. This is more pronounced in small diameter bones like the forearm. Therefore, when inserting self-tapping screws it is recommended that the screw chosen should be 2 mm longer than the actual measured length to maximize the pull-out strength (**Fig 3.2.1-7**) [5].

Removal of self-tapping screws may be difficult when the cutting flutes are filled by bony ingrowth, or if the friction between screw and bone surfaces is high.

To avoid problems with screw removal the surgeon should try to disengage bone in the flutes by first slightly tightening the screw, thereby shearing off the ingrown bone from the cutting flutes. Thus, the first turn should be clockwise followed by anticlockwise removal of the screw.

The obvious advantage of using self-drilling screws is their ease of application. However, this is offset by the fact that advancement of the drill bit and of the thread must be compatible and synchronous. Many self-drilling screws fail to offer good purchase because the pitch of their thread requires rapid progression of the drill-bit tip of the screw, which often cannot be achieved. A further disadvantage of self-drilling screws is that measurement of the proper screw length is not possible.

Therefore, most self-drilling screws are also cannulated screws. A guide wire is used first to predetermine the direction of the screw and to help with measurement. The self-drilling screw is then introduced and inserted over the guide wire, which is subsequently removed once the screw is in the desired place.

The use of bicortical, self-drilling screws with a long, sharp protruding tip that may damage nerves, vessels, or tendons is not recommended.

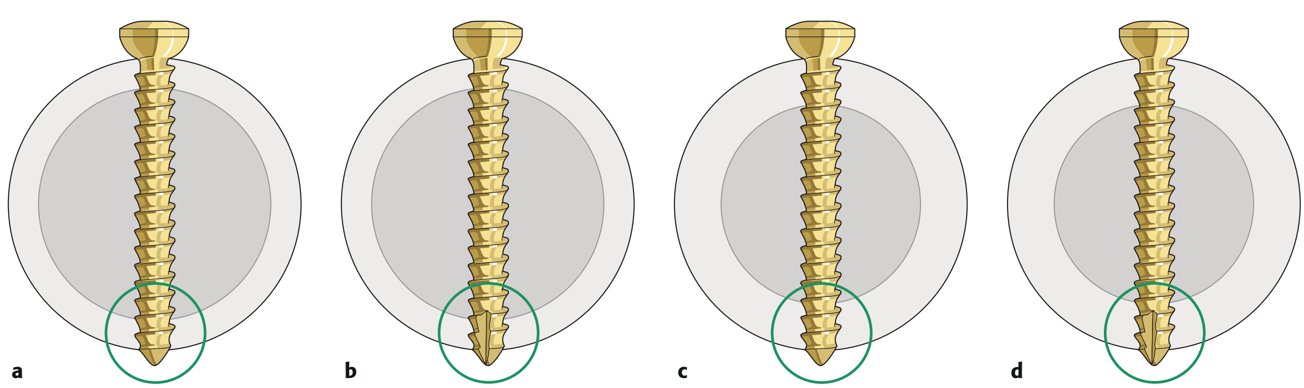


Fig 3.2.1-7a–d Self-tapping screws.
a–b When using self-tapping screws in bones with a thin cortex, it is essential to make sure that the tapping flutes pass the cortex to increase the pullout strength of the screw.
c–d In thick cortical bone, the pullout strength may not be affected significantly when a proper size self-tapping screw is used in comparison to a nonself-tapping screw.

The use of self-drilling/self-tapping monocortical LHS has been associated with failure of the screw. Therefore, the screw should be advanced until it engages on the far cortex without protruding out (**Fig 3.2.1-8**).

1.5 Screw function

A screw can be used to perform different functions depending upon the surgical plan **Table 3.2.1-1**

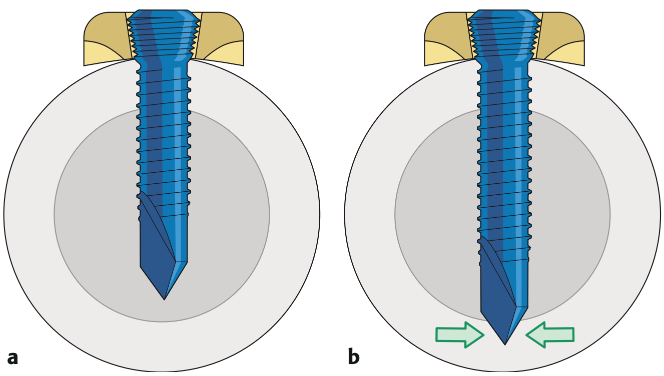


Fig 3.2.1-8a–b Self-drilling screws.
If the screw is introduced only a short distance inside the bone, there is risk of loosening of the screw with increased loads (**a**). When using these screws, it is noted that the tip is sharp and it can injure soft tissue beyond the cortex if it protrudes through the far cortex. This screw type should only be introduced deep enough to engage into the far cortex (**b**).

2 The lag screw

2.1 Interfragmentary compression

2.1.1 Application of a fully threaded screw as a lag screw

A fully threaded screw can be used as a lag screw, provided that the thread does not engage the cortex close to the screw head (near cortex).

Function		**Clinical example**
Name	**Mechanism**	
Plate screw	Preload and friction is applied to create force between the plate and the bone	Forearm LC-DCP
Lag screw	The glide hole allows compression between bone fragments	Fixation of a butterfly or wedge fragment or medial malleolus fracture
Position screw	Holds anatomical parts in correct relation to each other without compression, ie, thread hole only, no glide hole	Type C malleolar fracture (diastasis screw) or type C articular fracture with defect of distal humerus
Locking head screw	Used exclusively with LCP/LISS; threads in the screw head allow mechanical coupling to a reciprocal thread in the plate and provide angular stability	LCP/LISS in osteoporotic bone
Interlocking screw	Couples an intramedullary nail to the bone to maintain length, alignment, and rotation	Locked femoral/tibial intramedullary nail
Anchor screw	A point of fixation used to anchor a wire loop or strong suture	Tension band anchor in a proximal humerus fracture
Push-pull screw	A temporary point of fixation used to reduce a fracture by distraction and/or compression	Use of an articulated compression device
Reduction screw	Conventional screw used through a plate to pull fracture fragments towards the plate; the screw may be removed or exchanged once alignment is obtained	MIPO technique to reduce multifragmentary fracture onto a LCP
Poller screw	Screw used as a fulcrum to redirect an intramedullary nail (chapter 3.3.1)	Proximal tibial fracture during intramedullary nailing

Table 3.2.1-1 Functions of screws.
Abbreviations: LCP, locking compression plate; LC-DCP, limited-contact dynamic compression plate; LISS, less invasive stabilization system; MIPO, minimally invasive plate osteosynthesis.

This principle technique is achieved by drilling a glide hole into the near cortex with a diameter slightly larger than the outer diameter of the screw thread. In the opposite or far cortex, a smaller hole is drilled using a drill guide that inserts into the glide hole. This is called the pilot hole. It is the same diameter as the core of the screw to be inserted. A self-tapping screw may be introduced to the pilot hole or a tap can be used to cut a channel for the threads of a screw. It is then called a threaded hole. When a fully threaded cortex lag screw is applied, it only has purchase in the thread hole and does not engage in the glide hole. As the head of the screw is pressed against the cortex, preload is created. The bone fragments are compressed as the screw is tightened, producing interfragmentary compression (**Fig 3.2.1-9**, **Video 3.2.1-1**).

2.1.2 Application of a partially threaded screw as a lag screw

This principle technique is indicated in cancellous bone. It is achieved by drilling a pilot hole into the near cortex, across the fracture and into the far cortex. The smooth shaft of the partially threaded cancellous screw serves as the gliding hole, the threaded part engages the far cancellous and cortical bone and, as the head is compressed against the near cortex; preload is created which results in interfragmentary compression (**Fig 3.2.1-10**).

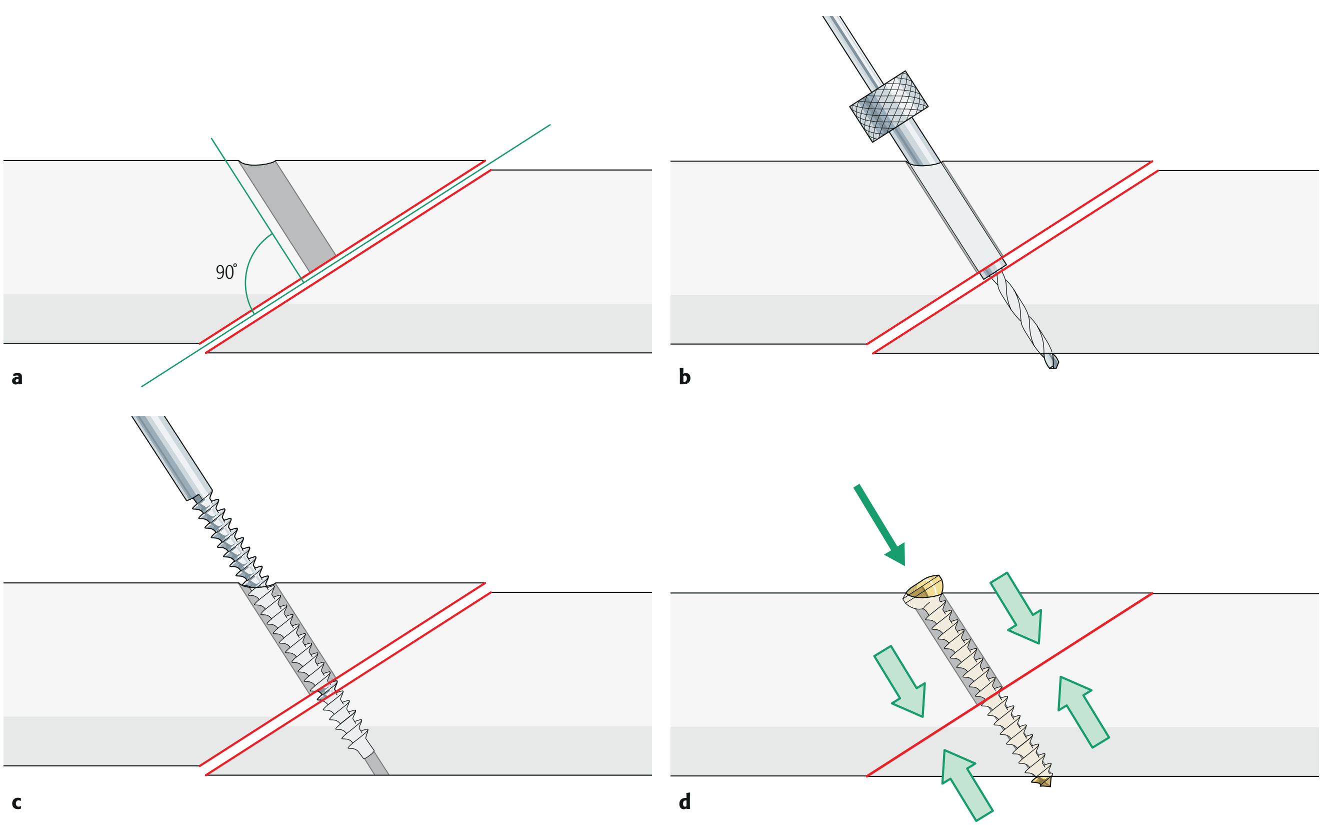


Fig 3.2.1-9a–d A fully threaded 4.5 mm cortex screw used to lag a fracture (function = interfragmentary compression).

- **a** Anatomical fracture reduction. The glide hole is slightly wider than the thread diameter of the screw. It is drilled at 90° to the fracture line.
- **b** The appropriate drill guide is placed within the glide hole. The pilot hole is drilled to the diameter of the core of the screw. The hole will be countersunk with the countersinking tool.
- **c** A tap is used to cut a channel for the threads in the pilot hole. This creates a thread hole. This step is omitted if self-tapping screws are used.
- **d** As the screw advances, the head engages the near cortex and creates preload. Further advancement of the screw creates compression at the fracture site (interfragmentary compression).

2.2 Screw-tightening and torque-limiting screwdrivers

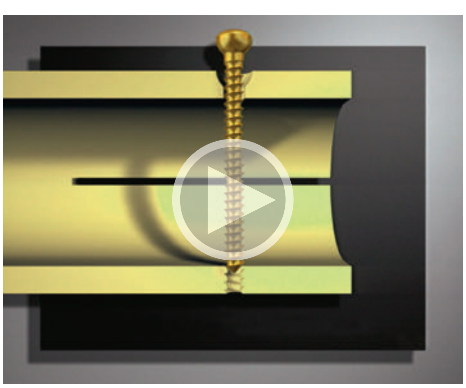
When an experienced surgeon tightens a screw to the degree which he considers optimal, the surgeon achieves torque that is close to the thread-stripping torque. Because screws produce high amounts of axial force, it does not make sense to tighten screws to this utmost limit. When the holding force of a screw is fully achieved by preload, there is little holding force left to sustain additional functional load. Historically, surgeons tried to achieve the utmost axial force, including repeated retightening. Today, the surgeon is advised to apply lag screws (and plate screws) at about 2/3 of the possible torque. It is also important that the surgeon appreciates that titanium gives less tactile feedback to the surgeon that stainless steel and extra care must be taken when inserting titanium screws (see chapter 1.3).

The LHS, LCP, and variable angle LCP (VA-LCP) lock upon tightening within the threaded plate hole and thus protect the screw thread and the bone. With these screws, a torque-limiting screwdriver must be used to prevent the screw heads from jamming. However, torque-limiting screwdrivers are of no practical use when applied to conventional screws because the quality and thickness of the bone exhibits large individual and topographic variations.

A variant of the LHS is the variable angle LHS which provides four options for threaded locking between the plate (VA-LCP) and the screw, forming a fixed angle construct at the desired angle. The head of the variable angle locking screw is rounded to facilitate various angles within the locking hole (see chapter 3.3.4).

2.3 Compression

Tests with expert surgeons have shown that 4.5 mm screws were routinely tightened to a torque that produced between 2,000–3,000 N of axial compression. In vivo measurements of compression applied to living bone demonstrated that the compression that was initially applied slowly decreases over months [6] but the compression outlasts the time required for the osteons to bridge the fracture gap and result in primary bone healing.



Video 3.2.1-1 Lag screw technique. The glide hole in the near cortex is wider than the diameter of the thread. The thread hole in the far cortex is the same as the core diameter of the screw and has been tapped.

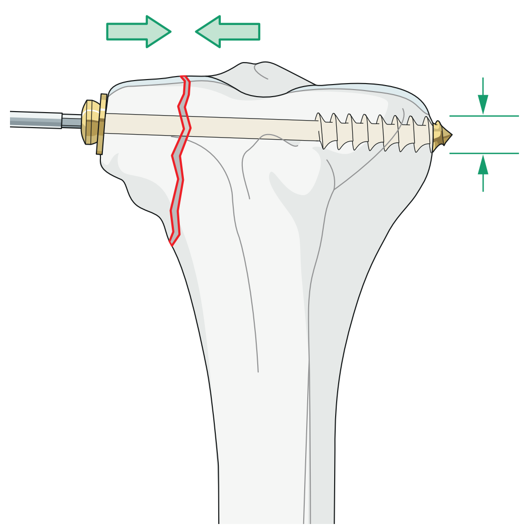


Fig 3.2.1-10 Compression of a partial articular fracture using a partially threaded 6.5 mm cancellous bone screw. The thread pulls the opposite bone fragment toward the head of the screw. The shaft of the screw does not transmit any great axial force between the shaft and the surrounding bone. The length of the screw shaft must be chosen so that the threaded part of the screw lies fully within the opposite bone fragment. To prevent the screw head from sinking into the thin cortex, a washer is used.

In vivo loosening of well-placed screws is induced by micromotion at the interface between thread and bone, and not by pressure (**Fig 3.2.1-11**) [7].

If the strain produced by micromotion is greater than the strain tolerance of bone, the screw will become loose and then place additional strain on the adjacent screw. There will be progressive loosening of the implant. This is a particular problem in osteoporotic bone that has low strain tolerance.

In most cases loosening is due to poor technique and common pitfalls include:

- Failure to plan
- Inappropriate implant positioning
- Failure to achieve anatomical reduction for absolute stability techniques
- Excessive force causing destruction of the screw-bone interface

In many cases, the overall stability will be irreversibly lost and the fracture may not heal.

2.4 Screw insertion

In conventional plating, the inclination of screws in relation to the long axis of the plate can be selected to provide an optimal lag screw position (**Video 3.2.1-2**), or to bypass either an area of comminution or a fracture line in the far cortex. The purchase of the screw in the far cortex then locks the inclination of the screw.

When monocortical screws are used, angular stability must be provided by the design of the screw head-to-plate locking process. A conical spiral thread provides this locking process. We use the general term of LHS for this type of construction. There are only a few indications for monocortical screws as their hold is inferior to bicortical screws; they are used most commonly for periprosthetic fractures where an intramedullary implant prevents the insertion of bicortical screws.

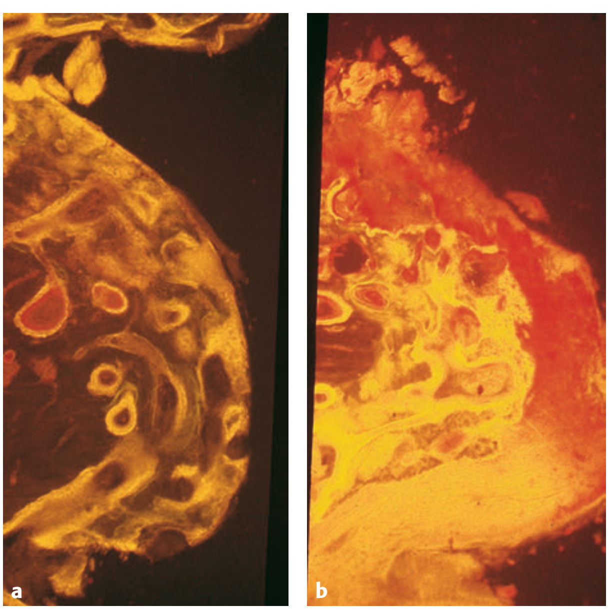


Fig 3.2.1-11a–b Mechanical loosening of a screw—biological reaction.
a Histological section of a well-fixed screw. There is close contact between bone and adjacent screw with bone remodeling.
b The appearance of the “thread” where the screw had been undergoing movement within a range of micrometers. Bone has been resorbed and replaced by fibrous tissue that no longer has holding power.

Video 3.2.1-2 The screw hole in the limited-contact dynamic compression plate (LC-DCP) allows inclination of screws and optimal lag screw placement.

Locking head screws cannot be used as lag screws.

An LHS can be inserted using minimally invasive techniques, but require careful planning and a thorough understanding of both the mechanics and biology of fracture fixation. Their use is described in detail in the chapter on locking plates (see chapter 3.3.4).

2.5 Modes of failure

Screws can fail because of axial pull out, bending forces, torque, or a combination of all these factors. Screws can fail during insertion when the surgeon attempts to apply maximum torque. While screws usually resist axial pullout well, most conventional screws poorly resist bending and torque due to their small core diameter. Based on the knowledge that the core diameter of a screw may be increased without unduly forfeiting the pull out force, the resistance to bending may be increased threefold by only a 30% increase of the core of a standard size screw.

The best implants tolerate intermittent peak (over-)load without irreversible loss of the bone-implant interface. While today's plates, intramedullary nails, and external fixators give way and spring back into their former shape, screws are less tolerant of peak load. With overload, the bony thread may strip and the screw will lose its holding power forever. This behavior must be considered when using lag screw fixation in isolation and in combinations of screws and flexible devices, such as intramedullary nails and external fixators.

3 Clinical applications of lag screws

3.1 Positioning of lag screw

Lag screws are most efficient when placed either perpendicular to the fracture plane or in an inclination halfway between the perpendiculars to the fracture plane and to the long axis of the bone (**Fig 3.2.1-12**). Whether the first or the second option is to be favored depends on the absence or presence of forces along the bone axis. The perpendicular position in relation to the fracture plane is, in most cases, simple to achieve and provides nearly optimal function of the lag screw. To improve stability in a long spiral fracture, several lag screws may be used. Their direction must follow the spiral plane of the fracture. This may cause considerable stripping of soft tissues and periosteum, and the preservation of the periosteal blood supply and biology must be considered when applying lag screws. Before inserting an inclined lag screw in diaphyseal bone, a countersink for the screw head should be prepared.

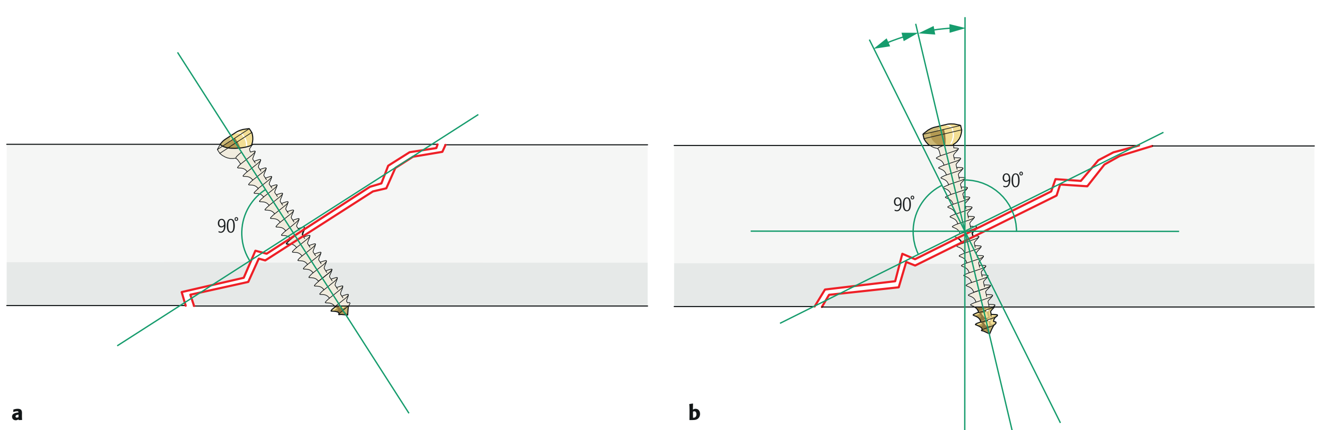


Fig 3.2.1-12a–b Optimal inclination of the screw in relation to a simple fracture plane.
a The lag screw is oriented perpendicular to the fracture plane. This is an ideal inclination in the absence of forces along the bone axis.
b An inclination halfway between the perpendiculars to the fracture plane and to the long axis of the bone is better suited to resist compressive functional load along the bone's long axis.

Single lag screws require protection by a plate—except close to a joint.

3.2 Lag screws in metaphyseal and epiphyseal regions

Articular and periarticular fractures need anatomical reduction and absolute stability to obtain and maintain perfect congruity of the joint. In this region, lag screw fixation is the predominant procedure. To prevent the screw head from sinking into the bone, a washer is often needed (**Fig 3.2.1-10**, **Video 3.2.1-3**). For postoperative functional treatment, most of these screw fixations will be supplemented by a protection or buttress plate. Locking head screws in combination with locking plates may provide angular stability when there are multiple fragments in the metaphysis. These screws cannot act as lag screws.

Video 3.2.1-3 Partially threaded cancellous bone screw used to lag a tibial plateau fracture.

4 References

1. **Haas N, Hauke C, Schütz M, et al.** Treatment of diaphyseal fractures of the forearm using the Point Contact Fixator (PC-Fix): results of 387 fractures of a prospective multicentric study (PC-Fix II). *Injury.* 2001 Sep;32(Suppl 2):B51–62.
2. **Tepic S, Perren SM.** The biomechanics of the PC-Fix internal fixator. *Injury.* 1995;26(Suppl 2):5–10.
3. **Krettek C, Krettek G.** Minimally invasive plate osteosynthesis . *Injury.* 1998;29(Suppl 3):C3–6.
4. **Baumgart FW, Cordey J, Morikawa K, et al.** AO/ASIF self-tapping screws (STS). *Injury.* 1993;24(Suppl 1):1–17.
5. **Taha W, Blachut P.** Pullout testing for self-tapping screws. Presented at: 50th Annual Orthopedic Research Day at University of British Colombia; May 2000; Vancouver, BC; 2000.
6. **Blümlein H, Cordey J, Schneider U, et al.** [Langzeitmessung der Axialkraft von Knochenschrauben in vivo.] *Med Orthop Tech.* 1977;97(1):17–19. German
7. **Ganz R, Perren S, Rueter A.** [Mechanical induction of bone resorption.] *Fortschr Kiefer Gesichtschir.* 1975;19:45–48. German.

5 Acknowledgments

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3.2.2 Plates

Mark A Lee

1 Introduction

While plating technology continues to evolve, the basic functions and applications of plates have remained essentially unchanged. With improvements and advances in the screw to plate interface options, plates are being used in an ever-widening array of applications. Conventional compression plate fixation, using techniques of absolute stability leading to direct bone healing, has generally been recommended for operative fracture treatment since Danis' and the AO group's pioneering work in the mid-20th century [1] and continues to have an important place in fracture treatment. Our improved understanding of the spectrum of stability and its influence on the mode of fracture healing, in concert with new screw interface technology and mixed screw type applications, has allowed us the opportunity to use plates in different ways than ever considered before [2–4].

Intraarticular fractures require anatomical reduction and absolute stability and plates are often used for fixation of the metaphysis. In these fractures, anatomical reduction is essential to minimize arthrosis, and callus formation is not desired. Diaphyseal fractures of long bones are often treated with intramedullary nailing but good indications for plating include the need for anatomical reduction (eg, forearm and fibular shaft) and the presence of a short distal or proximal fragment, which makes nailing technically difficult. Plate osteosynthesis may be preferred to external fixation in some polytrauma patients and in some cases of nonunion, especially in the presence of deformity.

Fixation with relative stability results in fracture healing via endochondral ossification with callus. Callus formation after attempts at fixation with absolute stability indicates a degree of instability that ultimately may lead to implant fatigue and failure (see chapter 1.3). Absolute stability results in direct fracture healing via remodeling and generally takes longer than healing by callus. A plate, in direct contact and pressed down onto the bone surface, can disturb blood flow to the underlying cortex. This may lead to local cortical necrosis [5], yet the clinical relevance of this necrosis is unclear. The process of bony remodeling and revascularization is slow and local osteoporosis is observed in cortical bone at the points of contact (footprints) with the plate.

The disturbance of the cortical blood supply can be decreased by minimizing stripping of the periosteum. The plate should be placed on top of it.

Due to its reduced area of contact with bone, the limited-contact dynamic compression plate (LC-DCP) appears to preserve the blood supply better than the original dynamic compression plate (DCP), an effect which is even more evident with locking plates, which do not rely on compression and friction between the plate and bone for stability [6]. It was previously theorized that plates weakened the local bone due to stress protection, a theory that is no longer widely accepted. It is more likely that disturbed vascularity results in slower remodeling of the cortex underneath a plate.

The classic plating technique, providing absolute stability, requires strict adherence to the principles of anatomical reduction and interfragmentary compression.

Errors of technique and misapplied principles may lead to complications, such as delayed healing, implant failure, and nonunion. These errors in technique are frequently related to failed or incomplete attempts at reduction during interfragmentary compression of simple fracture patterns (type A) or misguided attempts to stabilize multifragmentary fractures (type C) with lag screws. Locking plate designs can create secure and stiffer neutralization in a wide range of bone qualities and these technical errors may occur more commonly [7] with these implants if the surgeon fails to understand the principles and fails to plan.

2 Plate designs

Many different plates have been developed, most of which may be used to perform different biomechanical functions, depending upon how the surgeon applies the plate.

The surgeon, not the designer of the plate, determines how a plate will function and how it will be applied.

This is a key element of preoperative planning. Any nonlocking plate can be used to provide any of the six key functions of a plate (**Table 3.2.2-1**). However, the design and application of the plate must take into account the biomechanical environment. Thus, a thin, one-third tubular plate is an excellent choice to protect a lag screw fixation of the lateral malleolus but is not strong enough to act as a bridge plate for a multifragmentary fracture at the same site.

This section discusses the design and application of the various plates available and helps guide the surgeon in selecting the correct plate during preoperative planning.

2.1 Limited-contact dynamic compression plate

The LC-DCP was introduced by Perren in 1990 **[6]** and has become the gold standard for plate fixation (**Fig 3.2.2-1**). The plate is available in two sizes, 3.5 and 4.5, which is determined by the thread diameter of the cortex screws used with the plate. The screw hole design allows for axial compression by eccentric screw insertion.

The LC-DCP can be used to provide six different biomechanical functions:
- **Compression**
- **Protection**
- **Buttress**
- **Tension band**
- **Bridging**
- **Reduction**

2.1.1 Design

Several changes in design have improved the LC-DCP compared with earlier designs (eg, DCP).

The area of plate-bone contact (the plate footprint) is greatly reduced in the LC-DCP. There is less impairment of the capillary network of the periosteum, resulting in a relative improvement of cortical perfusion.

This reduces bone resorption underneath the plate. Moreover, the structured geometry of the undersurface of the plate results in an even distribution of stiffness, making contouring easier, and minimizing the likelihood of bends in the plate being concentrated (**Fig 3.2.2-2**). When using the

Plate function	Biomechanics	Example of application
Compression	The plate produces compression at the fracture site to provide absolute stability.	Simple transverse humeral fracture
Protection	The plate neutralizes bending and rotational forces to protect a lag screw fixation.	Simple oblique radial fracture
Buttress	The plate resists axial load by applying force at 90° to the axis of potential deformity.	Lateral tibial plateau fracture
Tension band	The plate is attached to the tension side of a fracture and converts the tensile force into a compressive force at the cortex opposite the implant.	Olecranon fracture
Bridging	The plate provides relative stability by fixation to the two main fragments, achieving correct length, alignment, and rotation. The fracture site is left undisturbed.	Multifragmentary ulnar fracture
Reduction	The plate assists in the direct reduction and overall position of fracture fragments that is either temporary or definitive. The plates do not harm fracture biology but are needed to provide accurate positioning of fracture fragments as definitive fixation can be achieved.	Multifragmentary proximal tibial fracture

Table 3.2.2-1 The six functions of a nonlocking plate.

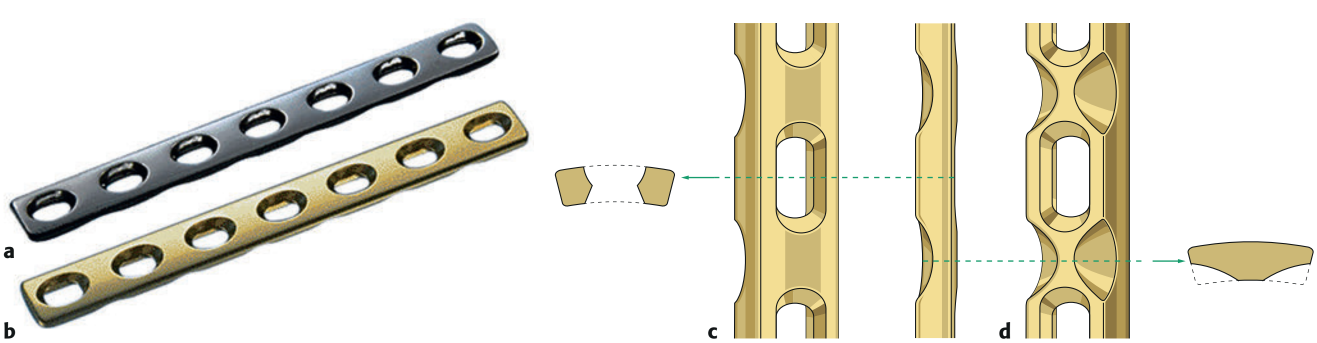


Fig 3.2.2-1a–d The LC-DCP is available in either stainless steel (**a**) or titanium (**b**). Its structured undersurface (**c–d**) allows limited contact between plate and bone, and there is an even distribution of holes along the plate.

bridging method, this distribution of stiffness results in a gentle elastic deformation of the entire plate without stress concentration at one screw hole. The cross-section of the plate is of a trapezoidal shape; hence, the bony ridges that form along the edges of the plate tends to be thicker and flatter, rendering them less prone to damage during plate removal.

The LC-DCP design is available in many sizes for different large and small bones with the broad 4.5 design used for the femur and the narrow 4.5 design used for the humerus and the tibia. The small 3.5 design is used for the forearm and the fibula.

The screw holes in the LC-DCP are best described as a portion of an inclined and angled cylinder. Like a ball, the screw head slides down the inclined shoulder of the cylinder (**Fig 3.2.2-3**). In practice, when the screw is inserted in such a hole and tightened, this results in movement of the bone fragment relative to the plate and consequently, compression

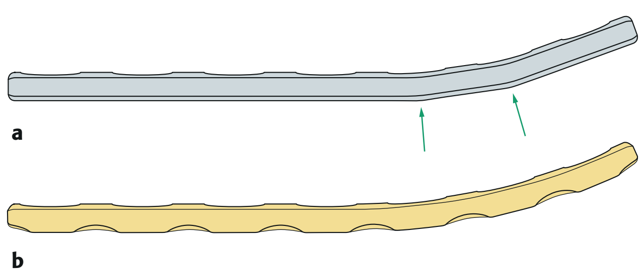


Fig 3.2.2-2a–b
a In DCP, the area at the plate holes is less stiff than the area between them. During bending the plate tends to bend only in the areas of the hole.
b The LC-DCP has an even stiffness without the risk of buckling at the screw holes.

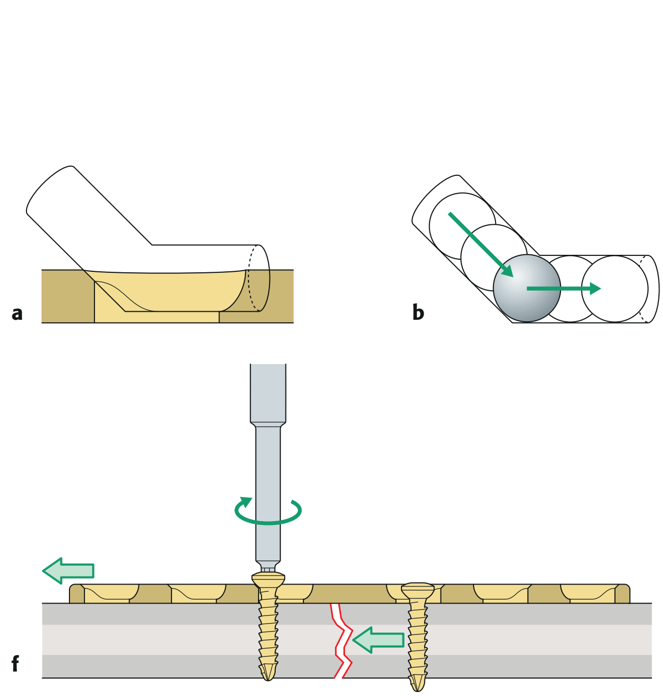
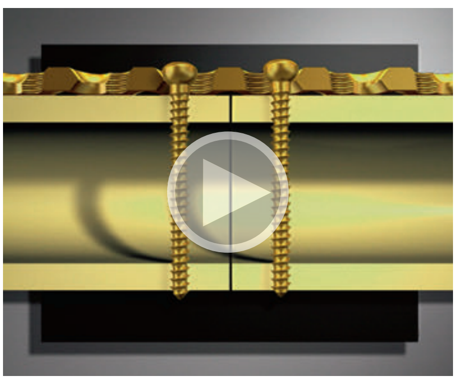


Fig 3.2.2-3a–f The dynamic compression principle.
a The holes of the plate are shaped like an inclined and transverse cylinder.
b–c Like a ball, the screw head slides down the inclined cylinder.
d–e Due to the shape of the plate hole, the plate is being moved horizontally when the screw is driven home.
f As the second screw is tightened, further horizontal sliding of the plate moves the bone toward the bone fragment, thereby achieving compression.

across the fracture site. The design of the screw holes allow for a displacement of up to 1.0 mm (**Video 3.2.2-1**). After the insertion of one compression screw, additional compression using one more eccentric screw is possible before the first screw is completely tightened (**Fig 3.2.2-4**). For axial compression over a distance more than 2.0 mm, the use of the articulated tension device is recommended (see section 3.2 in chapter). The oval shape of the holes allows 25° inclination of the screws in the longitudinal plane and up to 7° inclination in the transverse plane (**Fig 3.2.2-5**).

2.1.2 Technique of application

The LC-DCP 4.5 is used with 4.5 mm cortex screws and 6.5 mm cancellous bone screws. The LC-DCP 3.5 is used with 3.5 mm cortex and cancellous screws.



Video 3.2.2-1 Eccentric positioning of a conventional screw in the combination hole of the LCP allows this plate to be used as a compression plate.

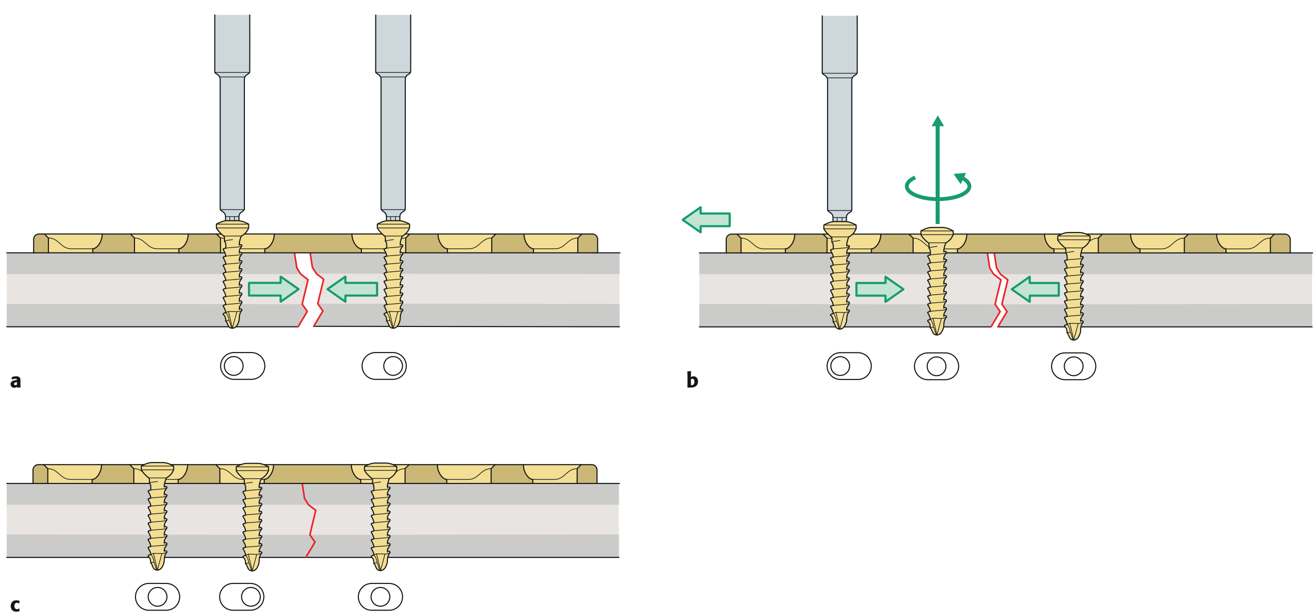


Fig 3.2.2-4a–c

- **a** Inserting one compression screw on either side of the fracture.
- **b** If after insertion of the two compression screws there remains a fracture gap, a third eccentrically placed screw may be inserted. Before this screw is tightened, the first screw has to be loosened to allow the plate to slide.
- **c** After that, the first screw is tightened again.

There are two DCP drill guides, one with an eccentric (load) hole and a gold collar, the other with a concentric (neutral) hole and a green collar, for each size of plate/screws (**Fig 3.2.2-6a–b**). Depending upon the intended function of the plate, the eccentric or neutral drill guide is chosen. If the screw is inserted in a neutral (green) position, the hole is 0.1 mm off-center and still adds a small amount of compression. The load (gold) drill guide contains a hole 1.0 mm off-center and should be positioned away from the fracture, so that when the screw is tightened the bone is displaced relative to the plate, applying compression to the fracture site (**Video 3.2.2-2**).

If the plate is intended to function as a buttress (see section 4.2 in this chapter), the universal drill guide (or sleeve) may be used, placing the screw at the opposite end of the hole. This prevents any gliding of the plate relative to the bone (**Fig 3.2.2-6c**).

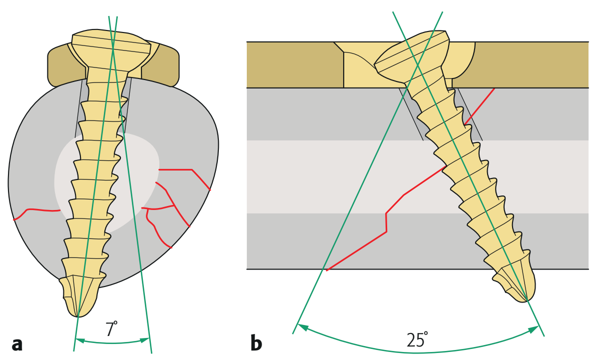
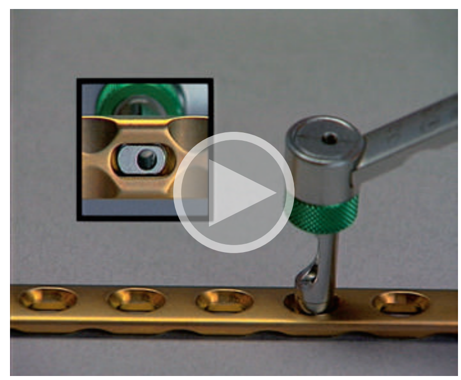


Fig 3.2.2-5a–b The shape of the holes of the DCP allows inclination of the screws of up to 7° in transverse direction (**a**) and of 25° in longitudinal direction (**b**).



Video 3.2.2-2 To drill an eccentric (load) hole and apply compression, the arrow on the drill guide must point toward the fracture.

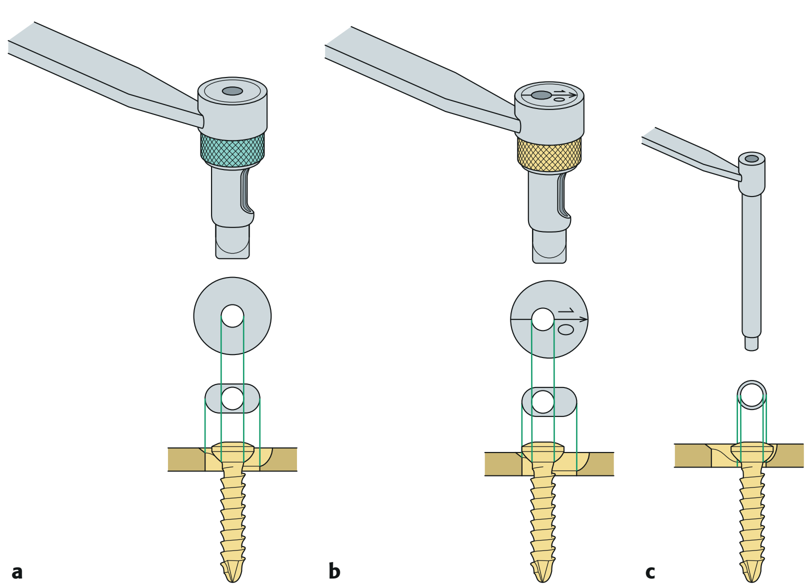


Fig 3.2.2-6a–c The application of the drill guides depends on the function the screw will have:

- **a** Neutral position (green end of the guide).
- **b** Compression (golden end of the guide).
- **c** Buttressing (universal drill guide).

The LC-DCP universal spring-loaded drill guide permits placement of the drill into the plate hole in a neutral or eccentric position. If the inner drill sleeve tube is extended (normal status of the drill guide) and placed against the end of the plate hole, an eccentric drill hole will result (**Fig 3.2.2-7a**). However, if the spring-loaded guide is pressed against the bone, the inner drill sleeve tube retracts and the rounded end of the outer tube glides down the slope of the hole into the neutral position (**Fig 3.2.2-7b**, **Video 3.2.2-3**).

2.2 Tubular plates

The one-third tubular plate exists only in the 3.5 version. Its counterpart in the 4.5 system is the semitubular plate. The one-third tubular plate is available in either titanium or stainless steel (**Fig 3.2.2-8a**). As it only has a thickness of 1.0 mm, its ability to confer stability is somewhat limited. However, it may be useful in areas with minimal soft-tissue covering, such as the lateral malleolus and the distal end of the ulna. Each hole is surrounded by a small collar (**Fig 3.2.2-8b**)

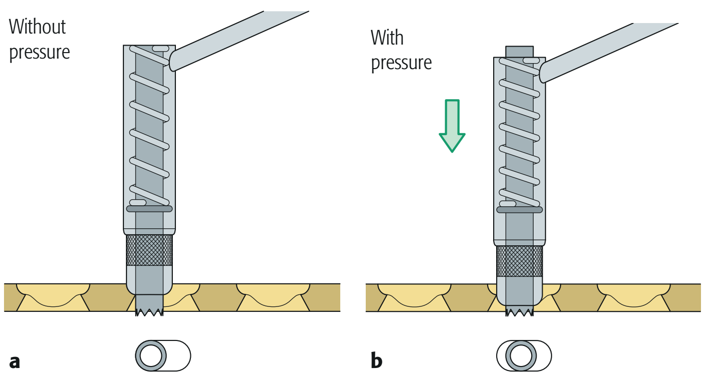
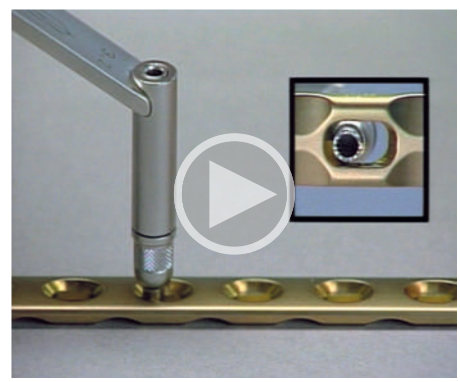


Fig 3.2.2-7a–b Application of the spring-loaded LC-DCP universal drill guide.
a Eccentric position.
b Neutral position.



Video 3.2.2-3 The LC-DCP universal drill guide, used without downward pressure, produces an eccentric hole.

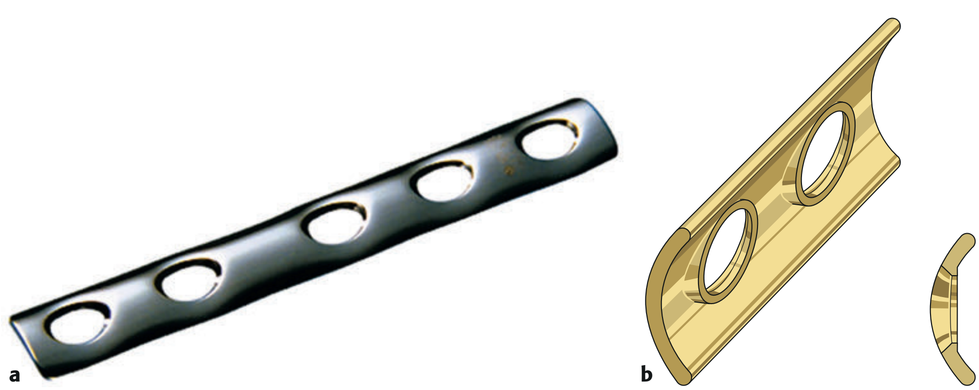


Fig 3.2.2-8a–e One-third tubular plates.
a Stainless steel one-third tubular plate.
b The collar around the hole of the one-third tubular plate prevents the screw head from protruding and secures plate-bone contact.

to prevent the spherical screw heads from penetrating the plate and producing cracks in the near cortex (**Fig 3.2.2-8c–d**). The oval shape of each hole allows a certain degree of eccentric screw placement to produce fracture compression (**Fig 3.2.2-8e**). This plate can also be stacked one upon another to improve stiffness yet maintain accurate bone contour and contact without the need for additional plate bending. The flexibility of the one-third tubular plate optimizes its function as a buttress (anti-glide) plate (**Fig 3.2.2-9**). This plate works well when applied at the apex of an oblique fracture since precise contouring is not necessary but critical, intimate plate-bone contact can still be achieved to produce an efficient buttress.

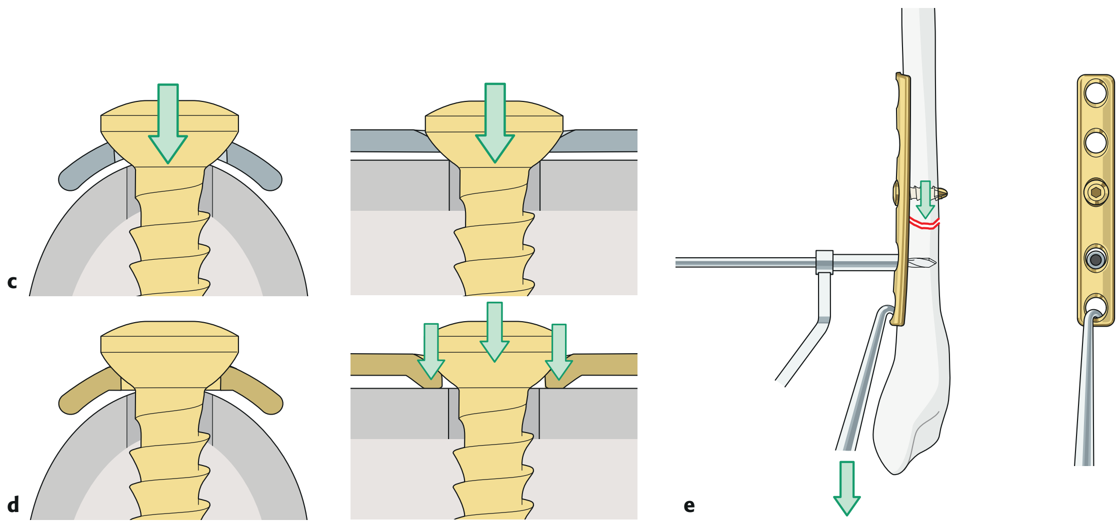


Fig 3.2.2-8a–e (cont) One-third tubular plates.
c Without a collar, the screw head would protrude through the plate, preventing good fixation.
d Due to the collar the plate-screw-bone coupling is improved.
e The oval shape of each hole allows a certain degree of eccentric screw placement to produce fracture compression, which can be augmented by pulling at one end of the plate.

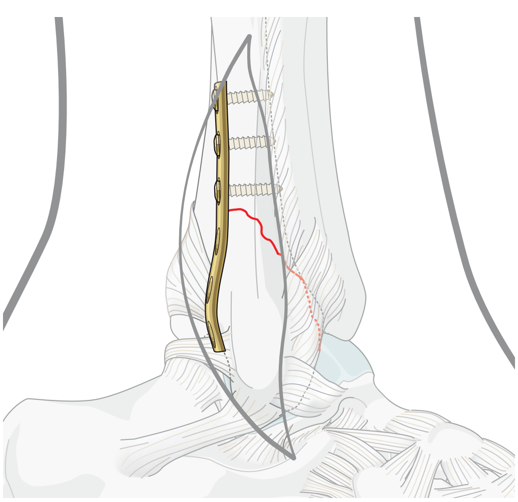


Fig 3.2.2-9 Buttress (antiglide) function demonstrated by a minimally contoured one-third tubular plate placed upon the posterior surface of the distal fibula with screws placed to reduce the oblique fracture.

2.3 Reconstruction plates

Reconstruction plates have deep notches on the edge of the plate. These notches are situated between the holes and allow accurate contouring of the plate in all planes (**Fig 3.2.2-10a**). Two plate sizes are available for use with 3.5 and 4.5 cortex screws. The plate is not as strong as the LC-DCP and may be further weakened by heavy contouring, so sharp bends in any direction should be avoided. The holes are oval to allow dynamic compression. These plates are especially useful in fractures of bone with complex 3-D geometry, such as the pelvis, acetabulum, distal humerus, distal tibia, and clavicle. Special instruments are available for the contouring of these plates (**Fig 3.2.2-10b**).

2.4 Locking plates

2.4.1 Design and biomechanics

Locking plate technology demonstrates some of the most recent advances in screw and plate interfaces. The locking compression plate (LCP) can be applied to function like any other plate, ie, it can provide compression, protection, bridging, and so on. Other locking plates, such as the less invasive stabilization system (LISS), act as internal fixators and can only provide a bridging function.

Conically threaded undersurfaces of the screw heads fit matching, reciprocal threads in the different locking plate designs, allowing screws to effectively bolt into the plate and bone (**Fig 3.2.2-11**). This has significant biomechanical implications. Because of angular-stable screws, the fixation does not require the plate to be compressed to the bone for stability. The combi-hole design also allows standard screws to be inserted into neutral or load holes and this allows the LCP to be used to perform any of the six biomechanical functions of a standard plate.

Locking plates can be used as internal fixators, especially the more rigid plate varieties, eg, LCP 4.5. Ideally, there is no contact with the periosteum. This provides relative stability and maximizes the possible blood supply to allow rapid, indirect healing through callus formation [2].

Angular-stable screws also allow load to be more evenly distributed along the entire fixation rather than being concentrated at a single bone-screw interface (**Fig 3.2.2-12**) **[8].** Failure of fixation with standard plates often starts at one screw, which may then propagate to other screws. Because a similar phenomenon does not occur with locking plates, they may be particularly useful in osteoporotic bone.

The LCP is versatile—it can be used to provide any of the six biomechanical functions of a nonlocking plate and can also be used as an internal fixator or a fixed-angle device.


a

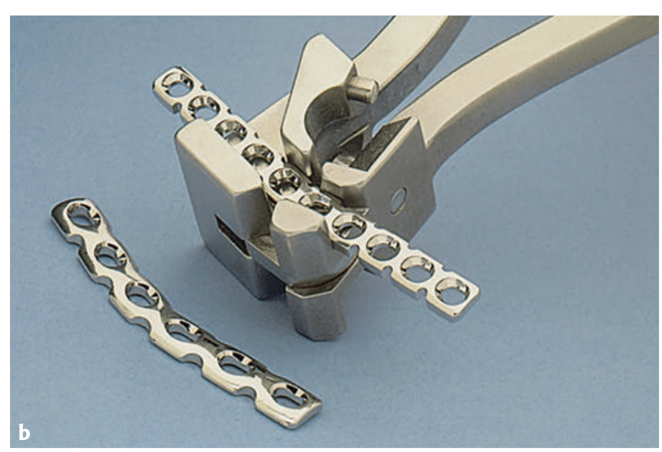

b

Fig 3.2.2-10a–b
a Reconstruction plate.
b The special bending pliers for the reconstruction plates: bending irons are available to twist the plate.

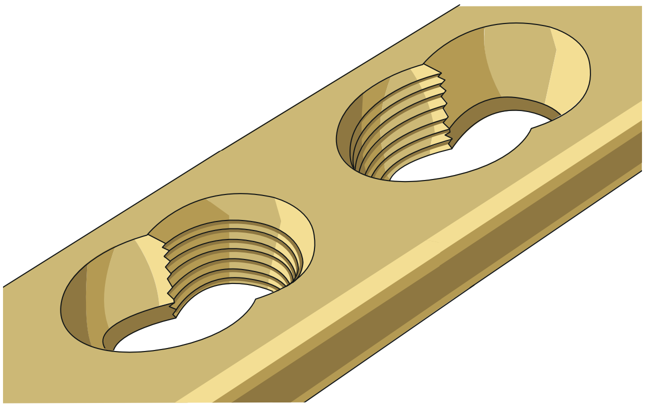
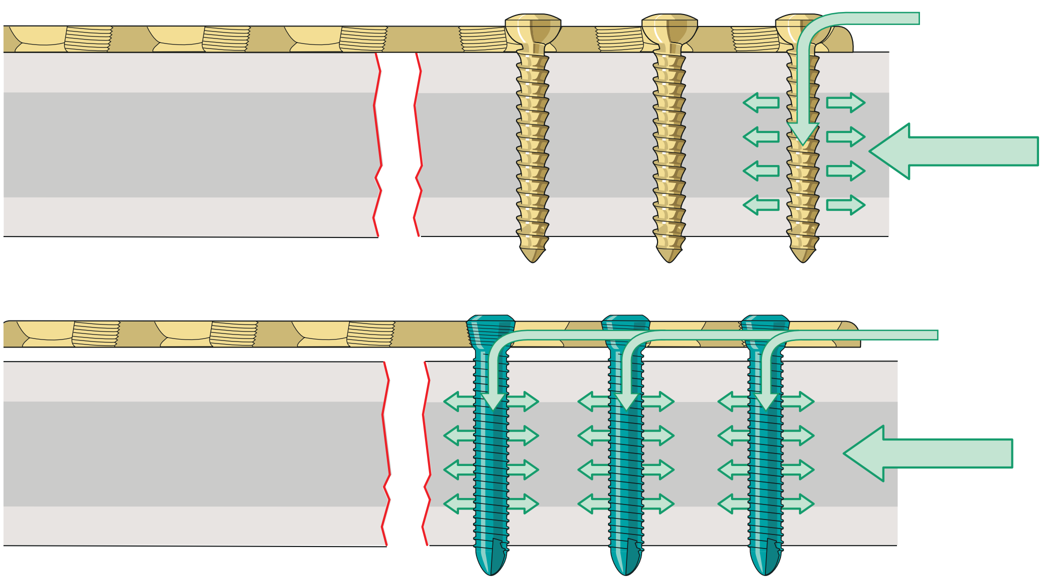


Fig 3.2.2-11 The LCP combination hole (combi-hole) allows conventional and locking head screws to be placed into the same implant but not into the same hole at once.



a

b

Fig 3.2.2-12a–b

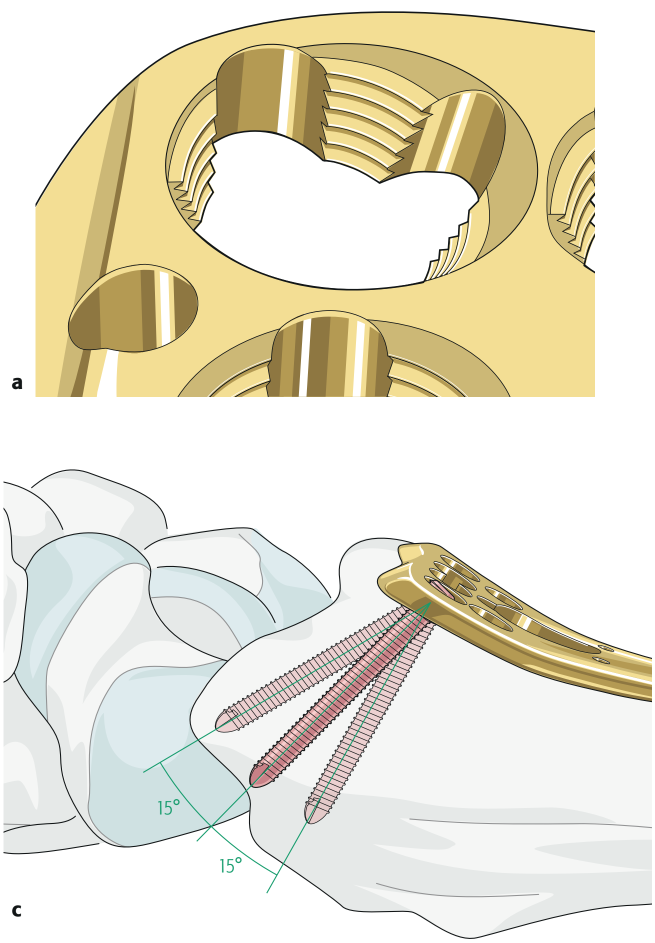
a Because a conventional screw head is allowed to toggle during loading, energy is dissipated at the bone-screw interface farthest from the fracture. Energy is concentrated at this level, shielding additional screws from load initially.

b In locking plates, the angular-stable screws (LHS) prevent load concentration at a single bone-screw interface by distributing load more evenly **[8]**.

The most recent development in locking plates is polyaxial screw technology. This plate-hole design allows for limited angulation of the screws within a defined radius (15° off the central/nominal axis) and still provides angular stability by a special threaded screw head and plate interface. It is best suited for periarticular fixation to maximize the purchase of screws close to the subchondral plate in a periarticular fracture while allowing the surgeon to position the screws so that the joint itself is not penetrated (**Fig 3.2.2-13**).

2.4.2 Technique of application

It is essential to understand that a locking head screw cannot be used as a reduction tool. Inserting a locking head screw will not realign a fracture fragment and it will not move the plate to improve reduction. Once a single locking head screw is applied through the plate on one side of a fracture, the position of the plate and that fracture fragment is fixed and cannot be adjusted.



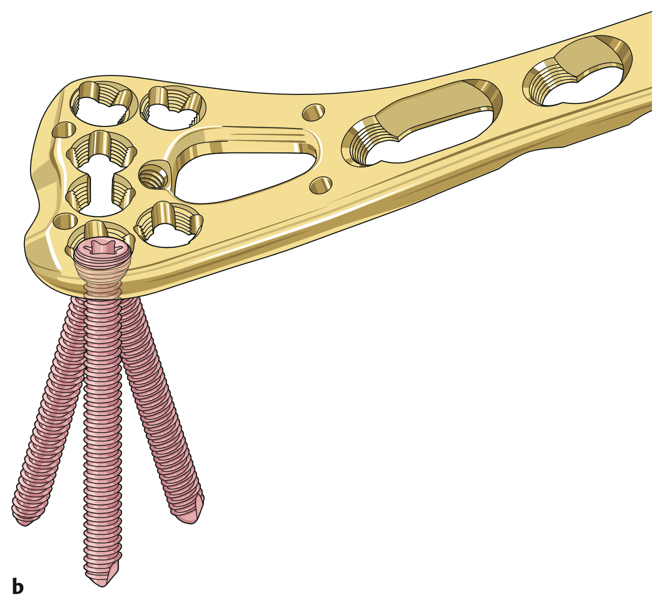


Fig 3.2.2-13a–c Variable angle technology.
a Four-column threaded screw hole in variable angle plate.
b–c Distal radial variable angle plate 2.4 showing 30° excursion of screws.

Careful preoperative planning is essential when using the LCP and this must include the order in which screws are applied. Before using a locking head screw, it is crucial that the final reduction is obtained.

Correct engagement of the locking mechanism requires a precise and predefined angle of insertion. Therefore, drilling is only performed after a threaded drill guide has been screwed onto the desired plate hole. Full seating of the threaded drill guide prevents later cross-threading of the locking head screw threads. Three methods of measuring screw length are possible:

- Removing the drill guide and using the standard, indirect measuring device
- Using a specific, indirect measuring device through the guide
- Measuring directly from the drill shaft

Variable angle locking screws must also be placed with precision. Most implant systems contain an angled guide to limit drill angulation. For any of the current designs, aiming of the screw path near the maximal suggested angulation may severely limit the amount of angular stability achieved. For most applications with these plates, the nominal screw axis (central or 0° off-axis) should be selected to optimize stability; however, angulation to the smallest acceptable deviation from the nominal axis may enhance fixation in osteoporotic bone.

The surgeon must be aware that fixation achieved is due to the screw-plate contact rather than screw-bone contact.

It is essential that the correct torque screwdriver is used to prevent overtightening of the screw.

Conventional and locking head screws can be used in the same fracture fragment but this requires careful planning.

Once a locking head screw has been inserted into a fracture fragment, no (additional) conventional screws should be inserted into this side of the fixation—only additional locking head screws may be used. "Reduce and lag first, lock second."

Poor bone quality is a clinical situation in which combination fixation may prove useful [9]. Initially, lag screws are placed in each segment to compress the fragments. Subsequently, the rest of the plate fixation is performed with locking head screws rather than conventional screws. These locking head screws support the friction fit established by the compression screws, without adding additional compression and risking implant cut-out by overtightening. Additionally, the angular stability may improve the overall strength of the construction by minimizing forces at the screw-bone interface. The biomechanics of this construction are untested and combining different principles in the same fracture fragment may not take full advantage of either principle [10, 11].

2.5 Special plates

Several special periarticular plates for specific locations have been developed (**Fig 3.2.2-14**). They are shaped anatomically, corresponding to the site where they are to be applied and many have combi-holes, making the plates versatile. These plates approximate average bone morphology and so there can still be a mismatch with individual bones. Depending upon the technique of application (use of locking versus nonlocking screws) manual contouring of these plates may be necessary. Bending near a locking screw hole must be done with caution; there may be deformation of the threads in the locking hole, which might change the screw head locking interface quality [12].

3.2.2 Plates

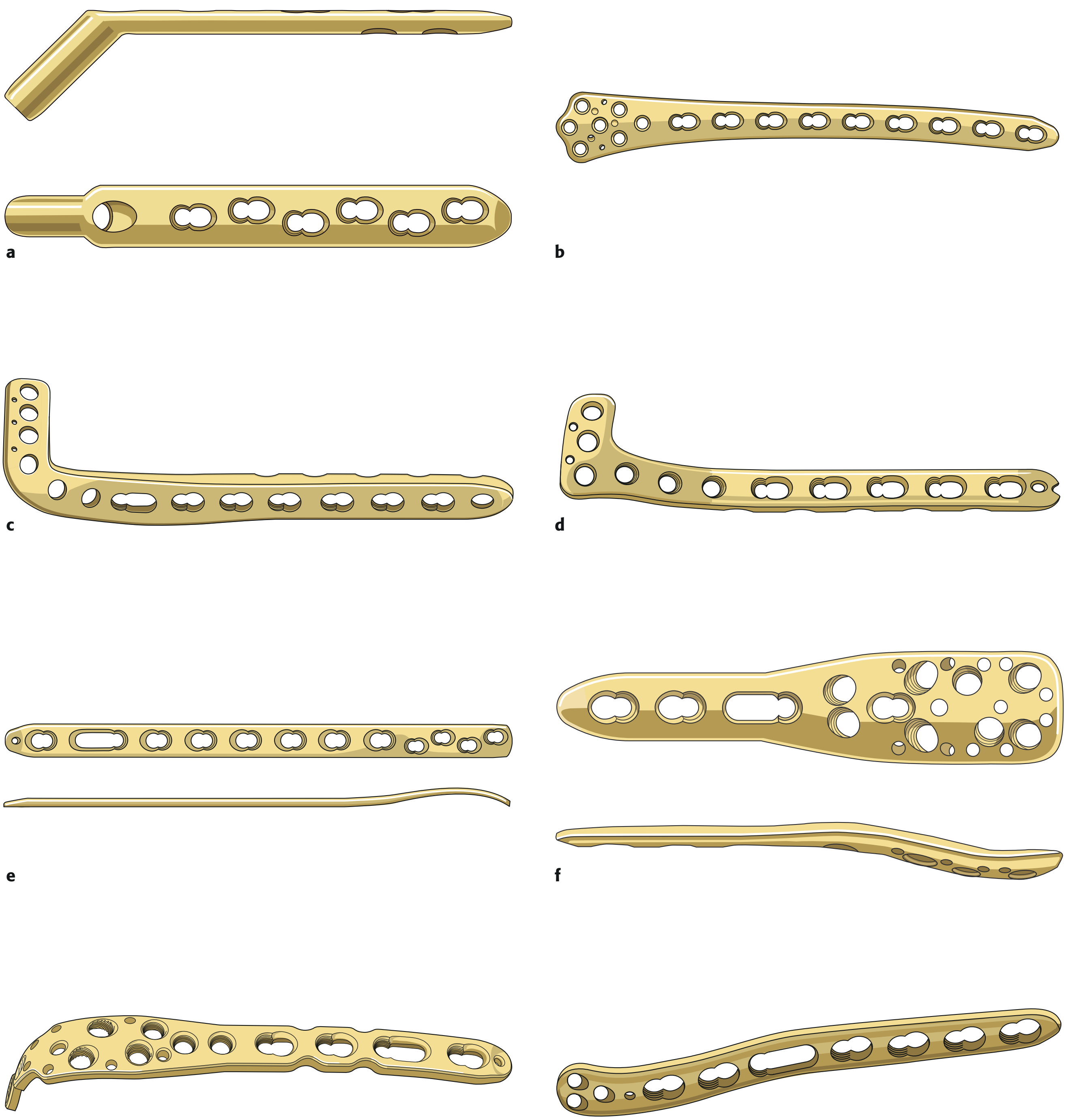


Fig 3.2.2-14a–m Selection of anatomically shaped plates.

a Side plate for DHS
b LCP-DF (distal femur)
c LCP anterolateral distal tibia
d LCP proximal tibia
e LCP metaphyseal plate
f PHILOS (proximal humerus)
g LCP olecranon plate
h LCP distal humerus

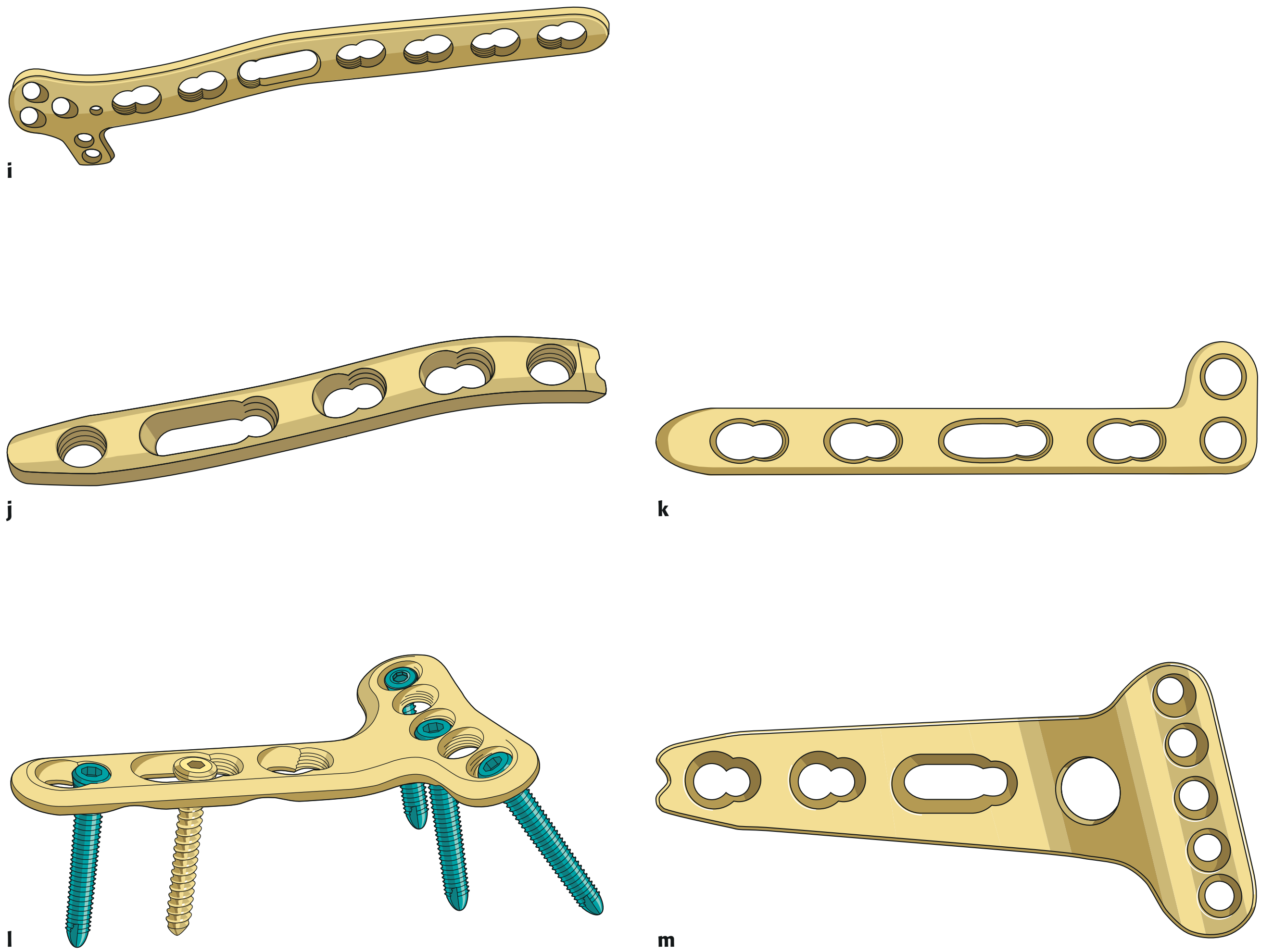


Fig 3.2.2-14a–m (cont) Selection of anatomically shaped plates.
i LCP lateral distal humerus
j–m LCP distal radius

3 Classic principle of absolute stability using plates

Absolute stability of plated fractures requires anatomical reduction and interfragmentary compression. This can be established by lag screws, axial compression by plate, or both. Static compression between two fragments is maintained over several weeks [13] and does not enhance bone resorption or necrosis (**Fig 3.2.2-15**). Fracture fragment interdigitation and compression reduces interfragmentary motion to nearly zero and allows for direct bony remodeling of the fracture (primary bone healing without callus).

To achieve absolute stability, compression must sufficiently neutralize all forces (bending, tension, shear, and rotation) along the whole cross-section of a fracture.

There are four ways of obtaining interfragmentary compression with a plate:

- Compression with the dynamic compression unit in a plate (LC-DCP)
- Compression by contouring (overbending) the plate
- Compression by lag screws through plate holes
- Compression with the articulated tension device

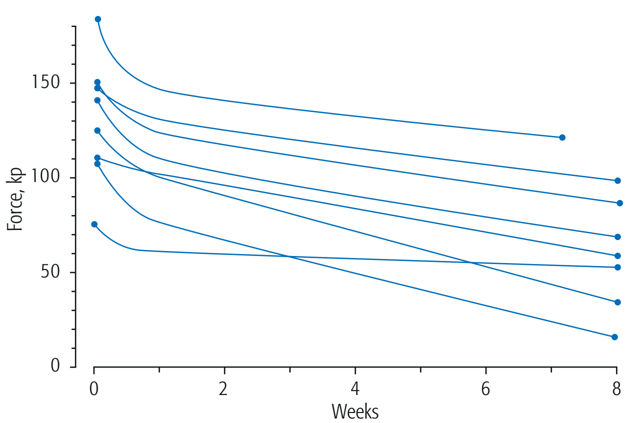


Fig 3.2.2-15 Compression applied to cortical bone in vivo. The compression force decreases slowly. This pattern of change in compression indicates that pressure necrosis with surface resorption in the compressed area does not occur.

3.1 Absolute stability by lag screw and protection plate

Simple fracture patterns treated with plate fixation are best reduced anatomically and fixed with a technique of absolute stability using a combination of lag screws and protection plate (**Fig 3.2.2-16**). A protection plate reduces the load placed upon an interfragmentary screw fixation, protecting it from failure. In metaphyseal split fractures, lag screw fixation often needs to be combined with a buttress plate to protect these screws from shearing forces. Plate contour should be accurate when using an LC-DCP for screw protection function, as a poorly contoured plate applied with nonlocking screws will cause translation of the bone toward the plate and create fracture displacement or loss of lag screw purchase. An LCP with all locking screws can also provide protection and may be a better choice when accurate plate contour cannot be achieved. A lag screw correctly inserted in good bone generates forces up to 3,000 N. Since the same effect cannot be brought about by any of the methods listed below, lag screws should be used whenever the fracture pattern permits.

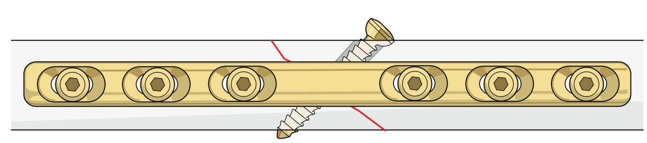


Fig 3.2.2-16 Lag screw osteosynthesis with a protection plate is shown. Interfragmentary compression is achieved by a lag screw. The function of the plate is to prevent the lag screw from bending, shear, and rotational forces. Lag screws may be placed independently or inserted through a plate.

A lag screw can be placed either by itself or through a plate. To avoid any additional soft-tissue stripping, placement through the plate is preferred.

In the case of a wedge fragment opposite to the plate, the fragment should be reduced with the aid of pointed hooks or a pointed reduction forceps (**Fig 3.2.2-17**). This has to be done carefully to avoid soft-tissue stripping.

3.2 Compression using the tension device

In transverse or short oblique fractures of the diaphysis, placement of a lag screw is not always possible. The articulated tension device (**Fig 3.2.2-18**) was developed to achieve adequate compression (more than 100 kp) in these instances. Furthermore, it is recommended for fractures of the femoral or humeral shaft, when the gap to be closed exceeds 1–2 mm, as well as for the compression of osteotomies and nonunions. Most plates have a notch at either end, which fits the hook of the tension device. Before use, the two branches of the tension device should be opened completely. After fixation of the plate to one main fragment, the fracture is reduced and held in position with a reduction forceps. The tension device is now connected to the plate and fixed to the bone by a short cortex screw. For the application of forces of 100–120 kp, or in osteoporotic bone, bicortical fixation is always recommended. In oblique fractures, to prevent displacement, the tension must be applied in such a way that the spike of the mobile fragment is pressed into the axilla that is formed by the plate and the other main fragment to

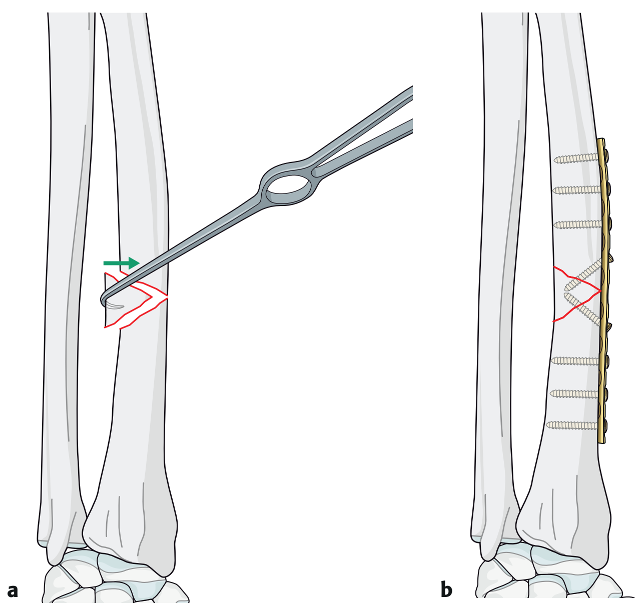


Fig 3.2.2-17a–b
a Bending wedge fracture reduced using dental pick to avoid soft-tissue stripping.
b Fixation with 2.7 mm lag screws through the 3.5 plate.

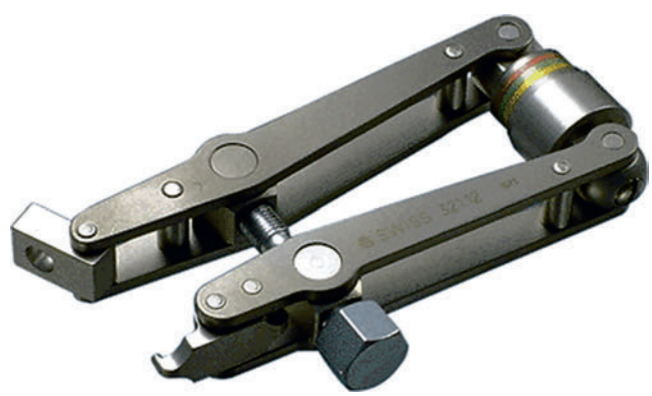
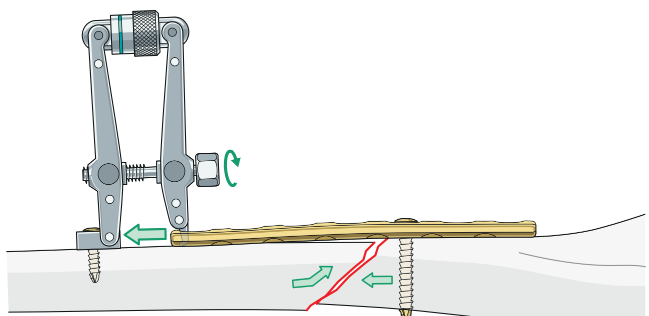
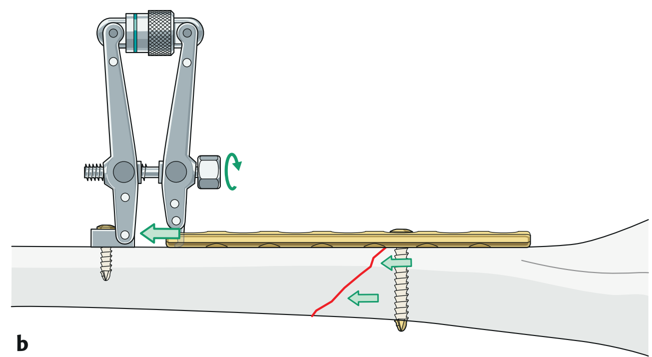


Fig 3.2.2-18 Articulated tension device. Depending on the position of the hook, the device can be used for distraction or compression.

which it has been fixed (**Fig 3.2.2-19**). Biomechanical studies have shown that the bending and rotational stability of such fractures is greatly increased if a lag screw is added through the plate once axial compression has been established (**Video 3.2.2-4**). For transverse fractures, it is essential that the plate is prebent at the fracture site to prevent eccentric tensioning and a gap at the opposite cortex (**Figs 3.2.2-20–21**).



a



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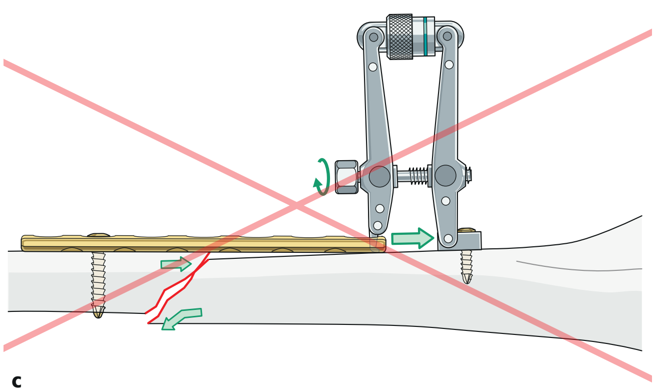
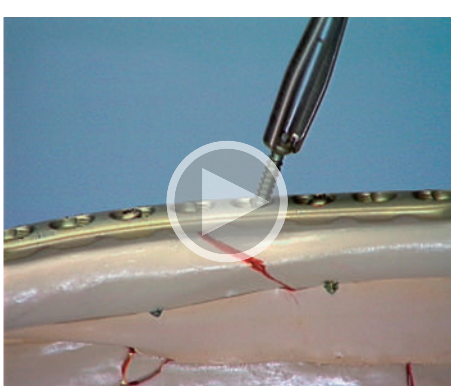


c

Fig 3.2.2-19a–c Application of the articulated tension device.
a–b In oblique fractures the tension device must be applied in such a way that the loose fragment locks in the axilla if compression is produced.
c This figure demonstrates the tension device applied in the wrong position.



Video 3.2.2-4 LCP applied to a simple radial fracture in conventional technique with a lag screw placed through the plate.

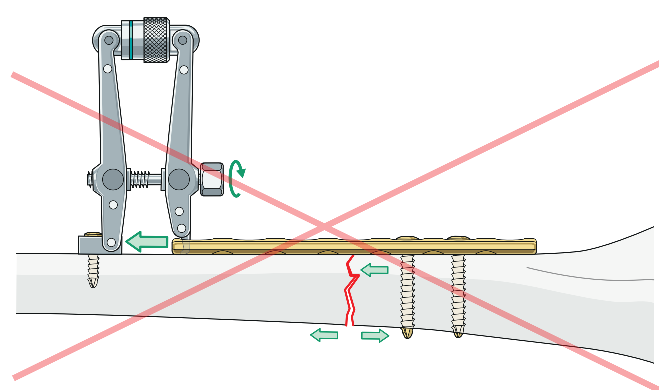


Fig 3.2.2-20 If a straight plate is tensioned on a straight bone, a fracture gap opens up due to the eccentric forces acting on the opposite side.

3.3 Compression by overbending

If a straight plate is applied to a straight bone, compressive forces are highest directly underneath the plate. At the far cortex a small gap results due to tension (**Fig 3.2.2-20**). This may prevent adequate concentric compression across the entire fracture surface. If the placement of an additional lag screw is not possible, prebending of the plate is essential (**Fig 3.2.2-21**). By applying tension, the overbent plate is straightened, which leads to compression of the opposite cortex, thereby adding to stability. There are special instruments available for prebending or contouring plates (**Fig 3.2.2-22**).

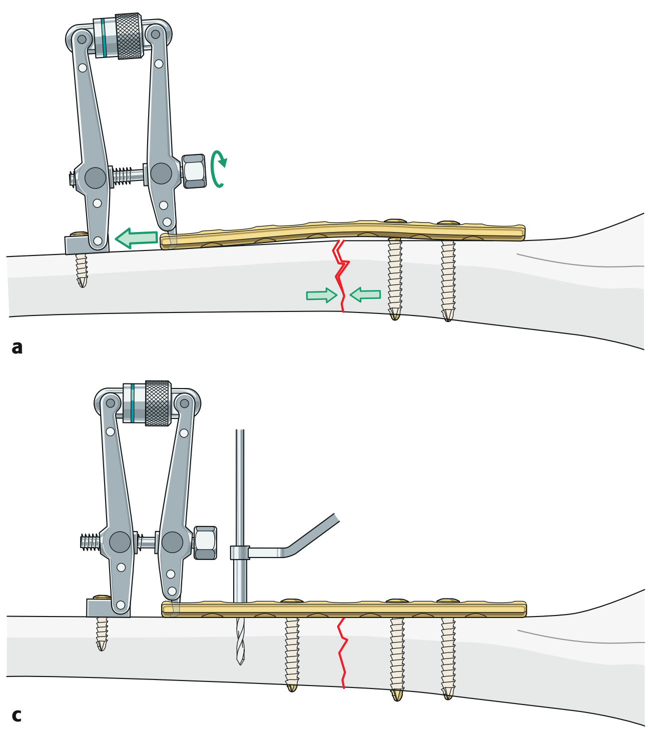


Fig 3.2.2-21a–c If the plate is slightly prebent before application (**a**), the gap in the opposite cortex disappears as compression is built up (**b**), so that finally the whole fracture is firmly closed and compressed (**c**).

Fig 3.2.2-22 The handheld bending pliers are useful and its correct use is shown in **Video 3.2.2-5**.

3.4 Compression using the LC-DCP (dynamic compression principle)

Axial compression can also be generated with the LC-DCP. However, the compression force achievable is lower than with the tension device. Prebending of the plate is necessary to obtain even distribution of the compressive forces.

3.5 Contouring of plates

Straight plates often need to be contoured before application to fit the anatomy of the bone. If this is not done, the reduction may be lost; especially if no lag screws are placed across the fracture. Anatomically shaped plates (see section 2.5 in this chapter) may also require fine contouring before application. This is best done with handheld bending pliers (**Fig 3.2.2-22**), the bending press, or bending irons (**Video 3.2.2-5**). If complex 3-D contouring is required, special flexible templates are available that can be modeled to the bone surface (**Fig 3.2.2-23**). Repeated bending back and forth should be avoided, as this weakens the plate. The LCP should be contoured by bending at an area away from the thread hole.

4 Different functions of plates

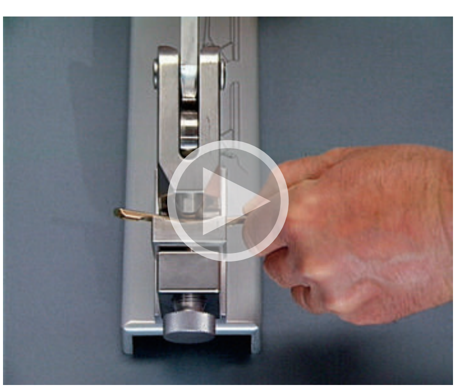
It is important to emphasize that each time a plate is used, the surgeon determines how a plate will function. Plates can be used in at least six different ways:

- Compression
- Protection
- Buttress
- Tension band
- Bridging
- Reduction

While the LCP also can be used as an internal fixator to bridge a fracture.

4.1 Compression and protection plates

The use of compression and protection plates has been described in detail (see section 3.1 in this chapter).



Video 3.2.2-5 Accurate contouring of plates requires correct use of tools, such as the bending press.

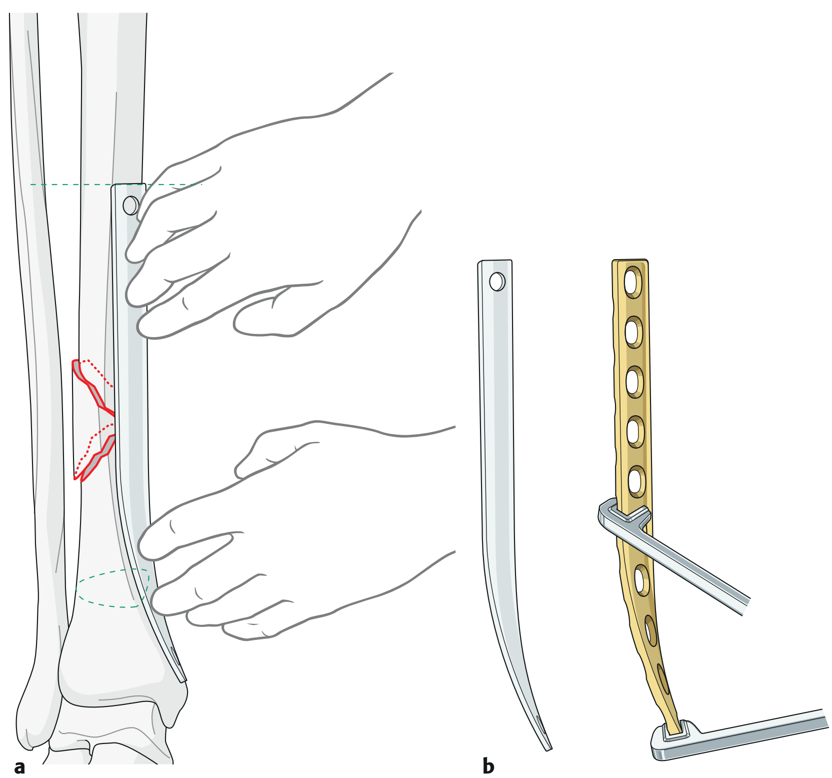


Fig 3.2.2-23a–b Flexible templates are used to facilitate plate contouring.

4.2 Buttress/antiglide plate

A buttress plate resists axial load by applying force at 90° to the axis of potential deformity.

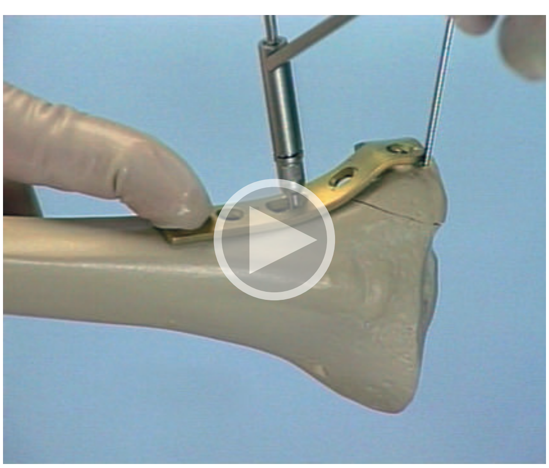
In a metaphyseal shear or split fracture, fixation with lag screws alone is often insufficient. A lag screw should therefore be combined with a plate with buttress function (**Video 3.2.2-6**). This will protect the screw from shear forces across the fracture. Plates can be used without lag screws to provide a buttress and, in plates with DC holes the screws should be inserted in the buttress position (**Fig 3.2.2-24**). A buttress is a powerful mechanical construct, as a visit to any medieval cathedral in Europe will demonstrate. If the surgeon has the option of using a buttress, it will usually provide the best fixation.

4.3 Tension band plate

The following four criteria must be fulfilled for a plate to act as a tension band:

- The fractured bone must be eccentrically loaded, eg, femur
- The plate must be placed on the tension (convex) surface
- The plate must be able to withstand the tensile forces
- The opposite cortex must be able to withstand compressive force

The last point is of paramount importance: anatomical reduction of the far cortex is essential and a tension band plate cannot function if the far cortex is in multiple fragments.



Video 3.2.2-6 For application of a buttress plate, the first screw must be eccentric to prevent sliding of the plate.

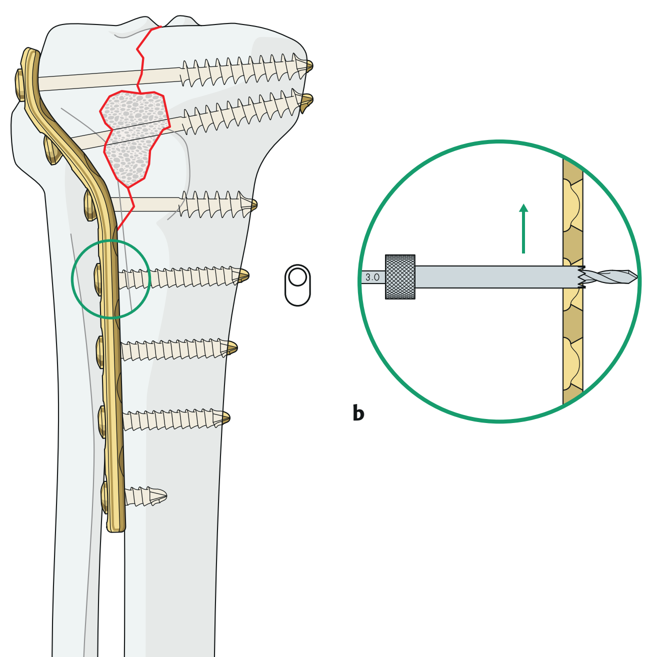


Fig 3.2.2-24a–b

a Application of the DCP in buttress function.

b To prevent any sliding of the plate, the screw is placed as proximal as possible in the hole.

The function of a tension band is to convert tensile force into compressive force. After fracture reduction, the opposite cortex must provide a bony buttress to prevent cyclic bending and failure of fixation.

A good example of an eccentrically loaded bone is the femur (**Fig 3.2.2-25**). If a plate is placed on the lateral (tension) side of a transverse fracture, the distraction forces are converted to compressive forces across the whole fracture interface provided the medial cortex is intact. If the same plate is placed medially, it cannot counteract the tensile force and the fixation will fail under load (see chapter 3.2.3).

4.4 Bridging plate

To respect the biology of a complex multifragmentary fracture and to minimize any additional soft-tissue injury, the bridge plating principle may be applied. Bridging plates provide relative stability and fracture healing occurs by callus formation.

The key concept of bridge plating is that the plate is fixed only to the two main fragments leaving the fracture zone untouched to maximize the blood supply.

If feasible, the fracture should be reduced indirectly and bridge plates should be applied through minimal exposure to restore length, axial alignment, and rotation [14]. Bridging plates are discussed in detail in chapter 3.3.2.

There are some important biomechanical principles to consider when using this technique. To maximize implant stability in this flexible fixation, long plates with few screws should be used to increase the lever arm and distribute the bending forces [15, 16]. A plate length of more than three times the fracture length in multifragmentary fractures, and more than eight to ten times the fracture length in simple fractures has been taught [9]. Screw to plate hole ratios of less than 0.5 create a long lever arm and decrease the bending loads on the distal screws [9]. In addition, a span of at least

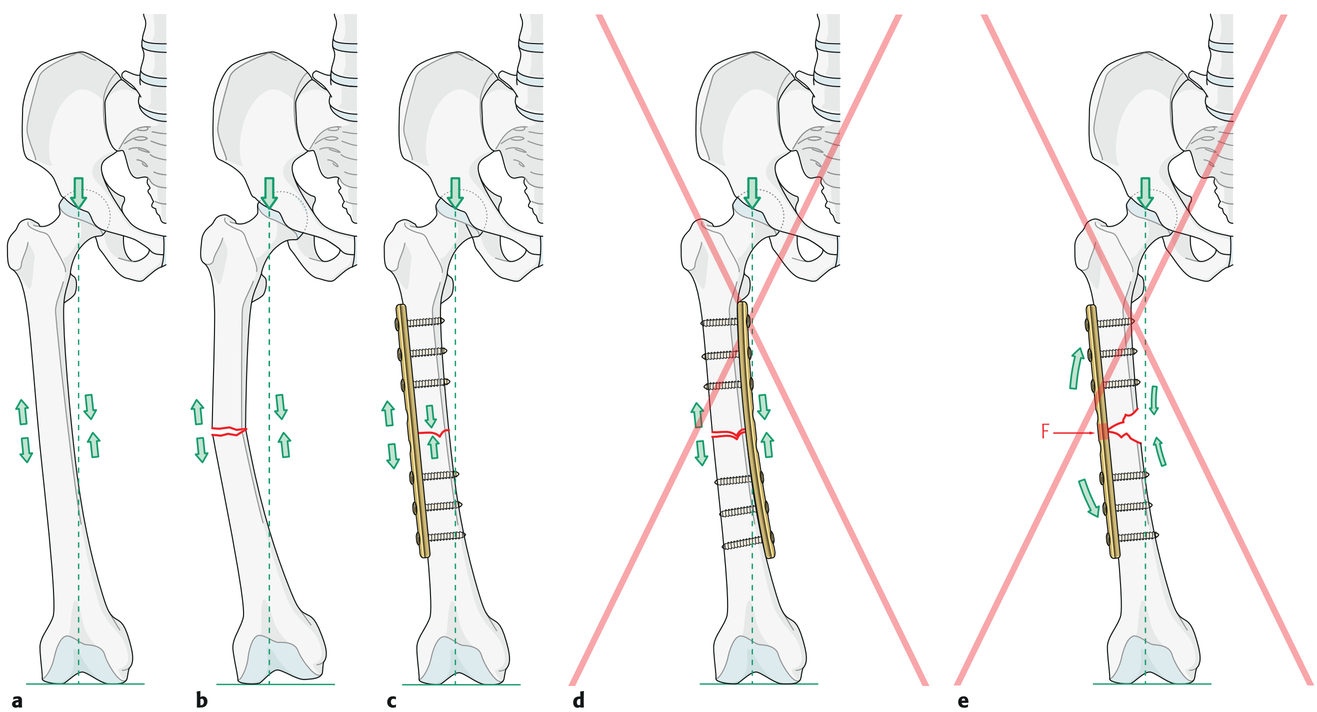


Fig 3.2.2-25a–e Tension band principle at the femur.

- **a** The intact femur is an eccentrically loaded bone with distraction or tensile forces laterally and compression on the medial side.
- **b** In case of a fracture, the lateral fracture gap opens, whereas the medial is compressed.
- **c** A lateral plate is under tension when loaded, thereby compressing the fracture gap, provided there is bone contact medially.
- **d** If the plate is placed onto the compression side, it is not able to prevent opening of the lateral gap (instability).
- **e** If the medial cortex is not intact, the tension band principle cannot work because of lack of a buttress (see chapter 3.2.3). Both these situations (**d–e**) must be avoided.

two or three screw holes should be left open over the fracture to decrease stress concentration (**Fig 3.2.2-26**, **Video 3.2.2-7**) [9, 15]. If the vascularity of the bone and surrounding soft tissue has not been overly disturbed, the physiological response to this relatively flexible construction is callus formation that bridges the fragments, as occurs in nonoperative treatment or after intramedullary nailing.

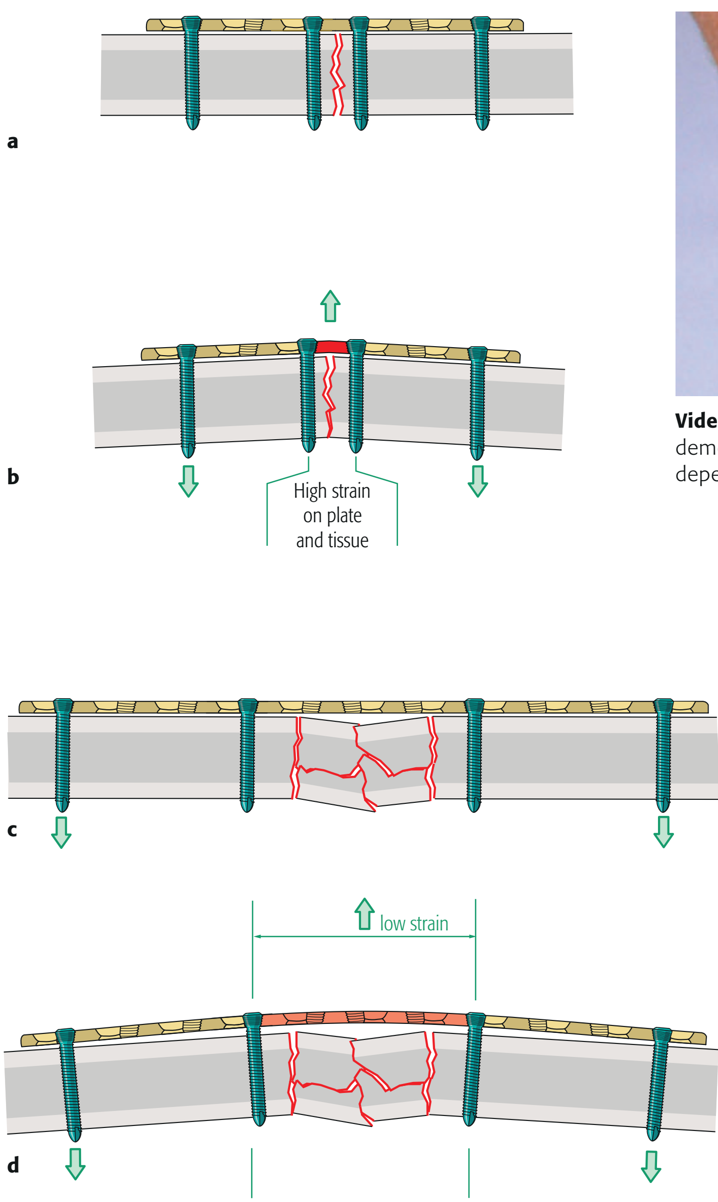
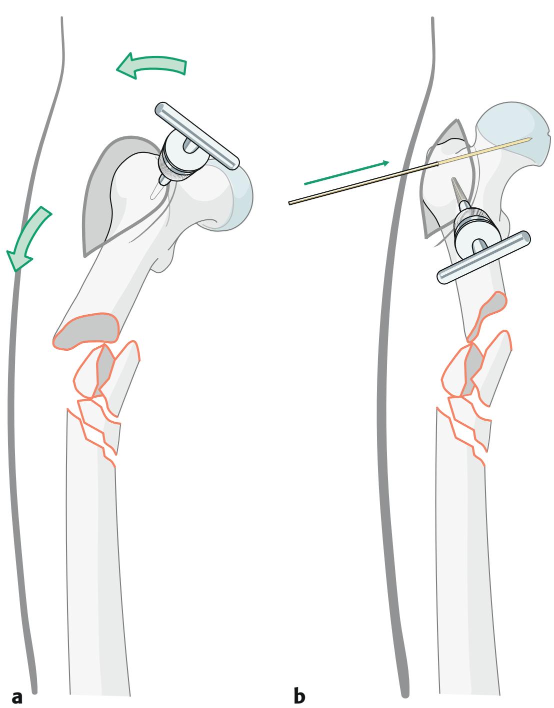


Fig 3.2.2-26a–d
a–b In a simple transverse fracture a short segment of the plate undergoes deformation (shown in red) due to high strain on the plate and tissue.
c–d In multifragmentary fractures, bridging is best done with long plates. In such a case the spanned segment is longer and a force such as shown in **a–b** is distributed over a longer distance. The strain on the plate is lower and its resistance to fatigue is higher [15].

Video 3.2.2-7 Credit card being stressed by two different methods demonstrates low strain and high strain in a dynamic system depending upon where the fixation is placed.

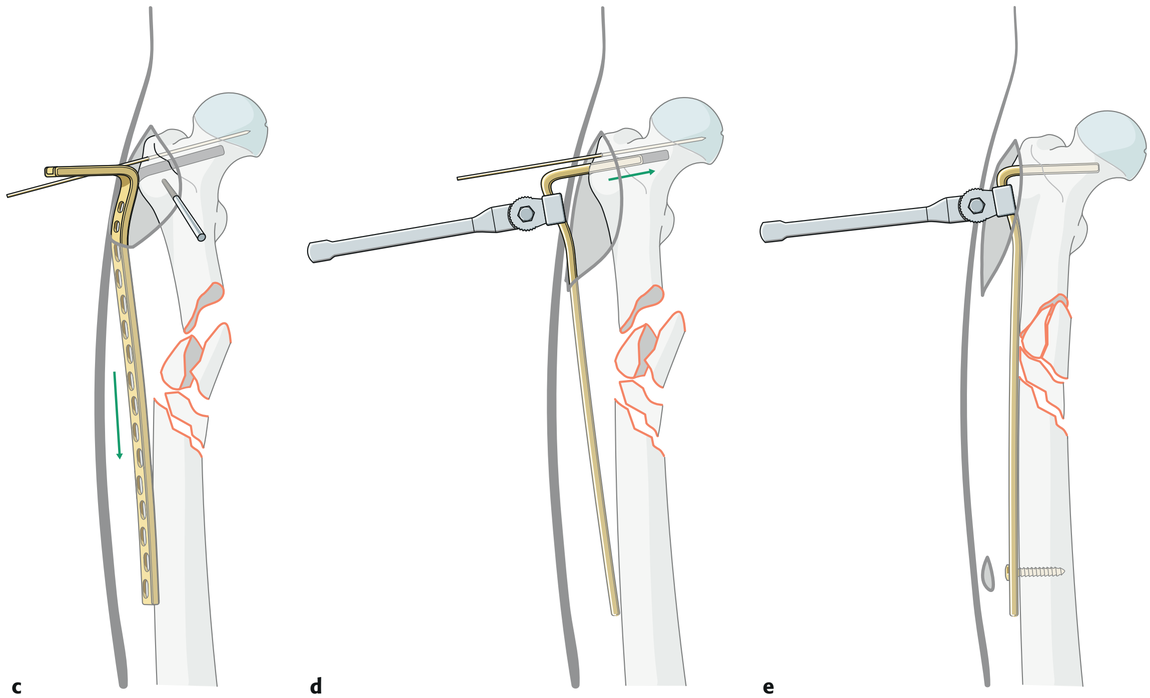
4.5 Reduction plate

The classic example of a reduction plate is the 95° angled blade plate applied with a plate first technique (**Fig/Animation 3.2.2-27**). With planning and accurate insertion, a fixed angle plate can correct multiple planes of displacement as it is transfixed above and below a fractured zone or deformity. Smaller caliber reduction plates (small fragment and mini-fragment size) are also used for reduction of transverse diaphyseal fractures, such as mid-shaft humeral fractures or clavicle fractures (**Fig 3.2.2-28**). Extreme care must be taken when using plates for reduction that significant additional dissection is not performed just to apply the reduction plates, as the least invasive reduction technique should always be selected. Small or mini-fragment plates are also frequently used to achieve and hold reductions of short metaphyseal segments or open diaphyseal fractures during intramedullary nailing procedures, especially in the tibia [17]. These plates should also be applied with caution as principles of preservation of local biology and soft-tissue management should be maintained. The decision to use locking or nonlocking plates should be based on bone quality for these applications; unicortical (intracortical) nonlocking screws can be placed to stay clear of the path an intramedullary nail then later converted to bicortical screws around the nail. The decision to leave the reduction plate should also be tailored to the application. Frequently plates used for metaphyseal reduction are left in place since they do not change the selected mode of stability (relative stability with intramedullary device). However, diaphyseal reduction plates are almost always removed since there is a risk that these plates might either fix a small gap between the bone segments or might limit the dynamic bone compression that is achieved with intramedullary load sharing of simple fracture patterns [17].



Fig/Animation 3.2.2-27a–e MIPO of proximal femoral fractures using the 95° condylar blade plate.

- **a** The Schanz screw is inserted to counteract the muscle pull and to keep the proximal femur in AP position. Care must be taken that the Schanz screw does not interfere with the preparation of the chiseled canal.
- **b** A guide wire is inserted at a 95° angle in the AP view with correct anteversion in the lateral view. The position of the guide pin is checked using image intensifier.



Fig/Animation 3.2.2-27a–e (cont) MIPO of proximal femoral fractures using the 95° condylar blade plate.

c After the canal has been prepared, the condylar plate is slipped under the vastus lateralis muscle with the blade facing laterally. The guide wire is kept as a reference for the direction of canal.

d–e The blade is turned 180° and inserted into the prepared canal using a plate holder. In some cases, the Schanz screw can be used to manipulate the proximal femur during blade insertion. Application of the distal screw will reduce the bone to the plate.

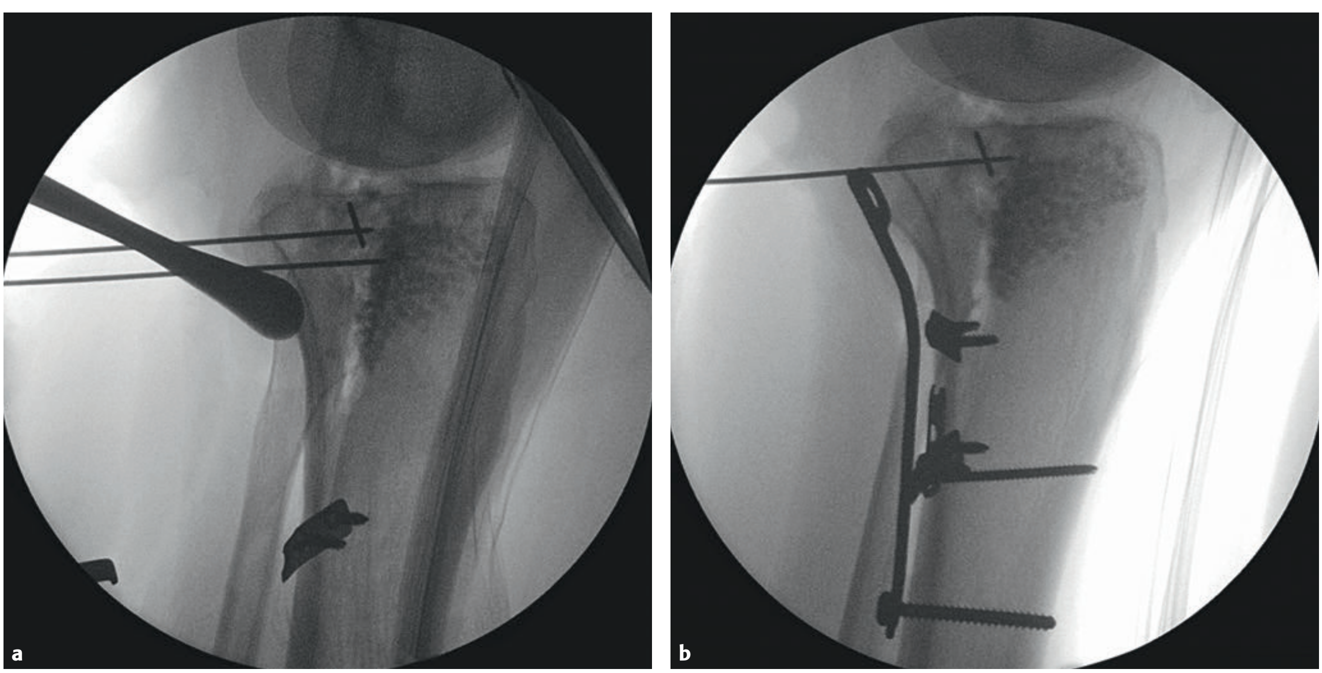


Fig 3.2.2-28a–b Lateral intraoperative images of posterior approach to a proximal tibial plateau fracture. Short, 3-hole one-third tubular plates have been applied with unicortical screws to help with reduction.

Classic references | Review references

5 References

1. **Miclau T, Martin RE.** The evolution of modern plate osteosynthesis. *Injury.* 1997;28(Suppl 1):A3–6.
2. **Perren SM.** Evolution of the internal fixation of long bone fractures. The scientific basis of biological internal fixation: choosing a new balance between stability and biology. *J Bone Joint Surg Br.* 2002 Nov;84(8):1093–1110.
3. **Schmal H, Strohm PC, Jaeger M, et al.** Flexible fixation and fracture healing: do locked plating "internal fixators" resemble external fixators? *J Orthop Trauma.* 2011 Feb;25(Suppl 1):S15–20.
4. **Bottlang M, Feist F.** Biomechanics of far cortical locking. *J Orthop Trauma.* 2011 Feb;25 Suppl 1:S21–28.
5. **Perren SM, Cordey J, Rahn BA, et al.** Early temporary porosis of bone induced by internal fixation implants. A reaction to necrosis, not to stress protection? *Clin Orthop Relat Res.* 1988 Jul;(232):139–151.
6. **Perren SM, Klaue K, Pohler O, et al.** The limited contact dynamic compression plate (LC-DCP). *Arch Orthop Trauma Surg.* 1990;109(6):304–310.
7. **Davis C, Stall A, Knutsen E, et al.** Locking plates in osteoporosis: a biomechanical cadaveric study of diaphyseal humerus fractures. *J Orthop Trauma.* 2012 Apr;26(4):216–221.
8. **Gardner MJ, Brophy RH, Campbell D, et al.** The mechanical behavior of locking compression plates compared with dynamic compression plates in a cadaver radius model. *J Orthop Trauma.* 2005 Oct;19(9):597–603.
9. **Wagner M, Frigg R.** *Internal Fixators—Concepts and Cases Using LCP and LISS.* New York: Thieme; 2006.
10. **Haidukewych GJ, Ricci W.** Locked plating in orthopedic trauma: a clinical update. *J Am Acad Orthop Surg.* 2008 Jun;16(6):347–355.
11. **Anglen J, Kyle RF, Marsh JL, et al.** Locking plates for extremity fractures. *J Am Acad Orthop Surg.* 2009 Jul;17(7):465–472.
12. **Gallagher B, Silva MJ, Ricci WM.** Effect of off-axis screw insertion, insertion torque and plate contouring on locked screw strength. *J Orthop Trauma.* 2014 Jul;28(7):427–432.
13. **Perren SM, Huggler A, Russenberger M, et al.** The reaction of cortical bone to compression. *Acta Orthop Scand Suppl.* 1969;125:19–29.
14. **Mast JW, Jakob R, Ganz R.** *Planning and Reduction Technique in Fracture Surgery.* 1st ed. Springer-Verlag: Berlin; 1989.
15. **Gautier E, Sommer C.** Guidelines for the clinical application of the LCP. *Injury.* 2003 Nov;34 Suppl 2:B63–76.
16. **Acharya AV, Evans SL.** Does placing screws off-centre in tubular bone alter their pullout strength? *Injury.* 2009 Nov;40(11):1161–1166.
17. **Dunbar RP, Nork SE, Barei DP, et al.** Provisional plating of type III open tibia fractures prior to intramedullary nailing. *J Orthop Trauma.* 2005 Jul;19(6):412–414.

6 Acknowledgments

We thank Dean Lorich and Michael Gardner for their contribution to this chapter in the second edition of the *AO Principles of Fracture Management.*

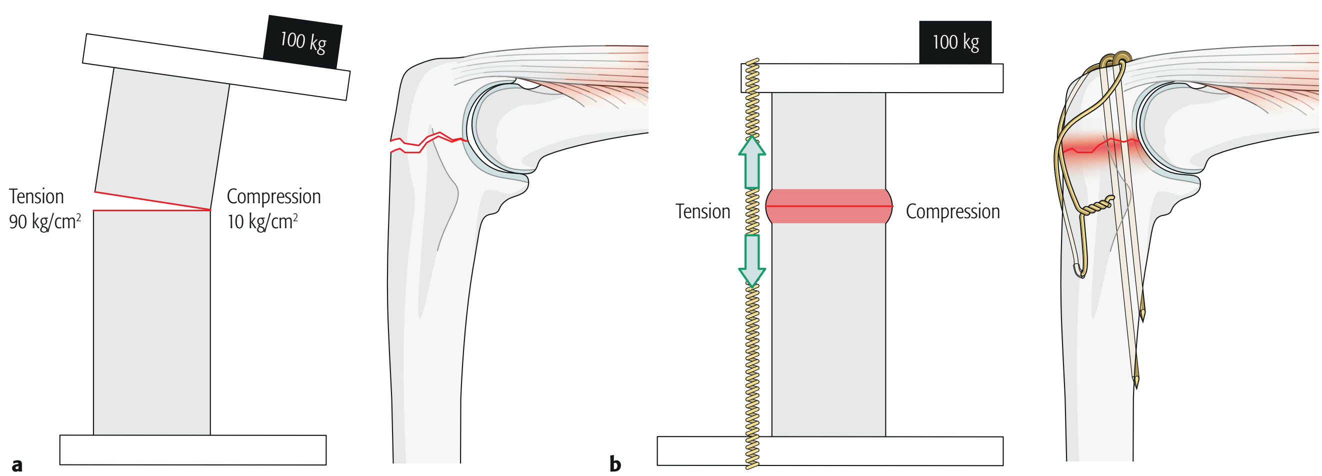
3.2.3 Tension band principle

Markku Nousiainen

1 Biomechanical principles

Early concepts of load transfer within bone were developed and described by Frederic Pauwels [1]. He observed that a curved, tubular structure under axial load always has a compression side as well as a tension side (**Fig/Animation 3.2.3-1**). From these observations, the principle of tension band fixation evolved.

A tension band converts tensile force into compression force at the opposite cortex. This is achieved by applying a device eccentrically, on the convex side of a curved bone.



Fig/Animation 3.2.3-1a–b The tension band principle.
a An eccentrically loaded bone has a tension and a compression side.
b A tension band converts tension into compression at the opposite cortex.

The concept can most easily be understood by examining the femur under mechanical load (**Fig 3.2.3-2**). If a fracture is to unite, it requires mechanical stability, which is obtained by compression of the fracture fragments. Conversely, distraction or tension interferes with fracture healing. Therefore, tension force on a bone must be neutralized or, ideally, converted into compression force to promote fracture healing. This is especially important in articular fractures, where stability is essential for early motion and good functional outcome. In fractures where muscle pull tends to distract the fragments, such as fractures of the patella or olecranon, the application of a tension band will neutralize

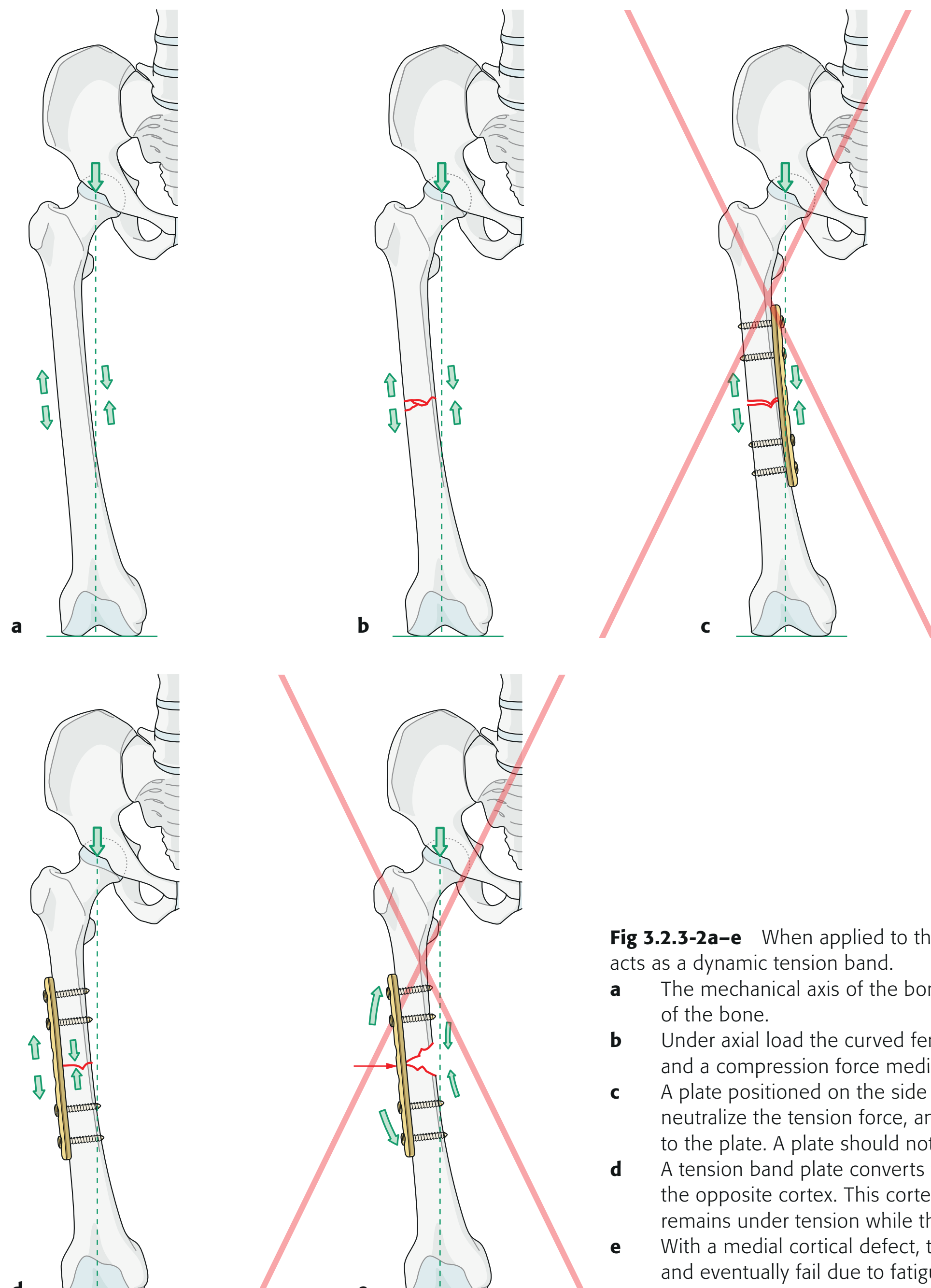


Fig 3.2.3-2a–e When applied to the tension side of the bone, a plate acts as a dynamic tension band.

- **a** The mechanical axis of the bone is not necessarily within the center of the bone.
- **b** Under axial load the curved femur creates a tension force laterally and a compression force medially.
- **c** A plate positioned on the side of compressive forces cannot neutralize the tension force, and gapping will be observed opposite to the plate. A plate should not be applied in this position.
- **d** A tension band plate converts tensile force into compression on the opposite cortex. This cortex must provide a buttress. The plate remains under tension while the bone is compressed.
- **e** With a medial cortical defect, the plate will undergo bending stresses and eventually fail due to fatigue at a specific point (arrow). A tension band plate should not be used in this situation.

these forces and even convert them into compression when the joint is flexed (**Fig 3.2.3-3a–b**). This is accomplished through the creation of a "hinge" at the side of the fracture occupied by the tension band construct. The subsequent application of distraction forces rotates the fracture around this hinge, producing a compression force opposite to it. Similarly, a bone fragment can be avulsed at the insertion of a tendon or ligament, as in the greater tuberosity of the humerus (**Fig 3.2.3-3c**), the greater trochanter of the femur, or the medial malleolus (**Fig 3.2.3-3d**). Here, too, a tension band can reattach the avulsed fragment, converting tensile forces generated by ligamentous pull into compression forces at the fracture surface.

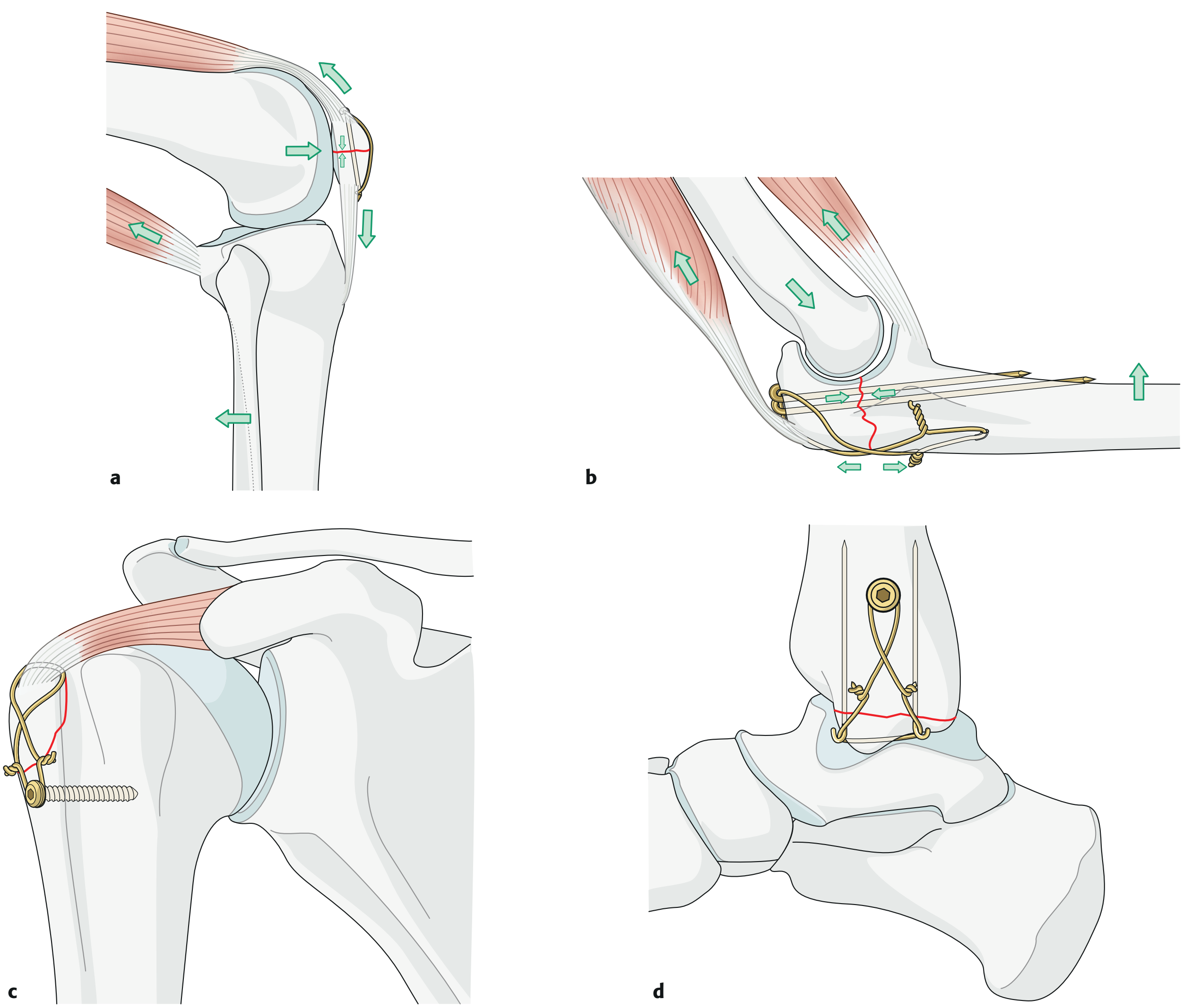


Fig 3.2.3-3a–d

a Tension band principle applied to a fracture of the patella. The figure-of-eight wire loop lies anterior to the patella and fracture. Upon knee flexion, the tensile force (between the quadriceps muscle and the tibial tuberosity) is converted into compression at the articular surface.

b In the olecranon fracture, the figure-of-eight wire loop acts as a tension band during flexion of the elbow. This is an example of a dynamic tension band.

c Application of the tension band principle at the proximal humerus for an avulsion of the greater tubercle. The wire loop is anchored to the humerus by a 3.5 mm cortex screw.

d Application of the tension band principle to the medial malleolus. The wire loop may be anchored to the tibia by a 3.5 mm cortex screw. This is an example of a static tension band.

2 Concepts of application

The tension band principle with wire loops is often applied to articular fractures of the patella and olecranon, converting tension from muscle pull into a compression force on the articular side of the fracture. In addition, small avulsion fractures may benefit from the principles of tension band fixation (**Fig 3.2.3-3c–d**).

The principle of tension band fixation with a plate can also be applied in diaphyseal fractures of curved bones, such as the femoral shaft. Application of a tension band construct to the tension side of the bone neutralizes distraction at this site, while promoting compression on the opposite side of the bone.

In curved long bones, the convex side of the diaphysis indicates the tension side.

Similarly, in delayed union or in nonunion, where the presence of angular deformity creates a tension side in the bone, adherence to the tension band mechanical principles is extremely important.

Whenever feasible, any internal or external fixation device should be applied to the tension side [2].

Bony union will then consistently occur. Loops of wire, cables, as well as absorbable or nonabsorbable suture material can function as a tension band. When appropriately placed, intramedullary nails, plates, and external fixators can also fulfill the function of a tension band (**Fig 3.2.3-4**).

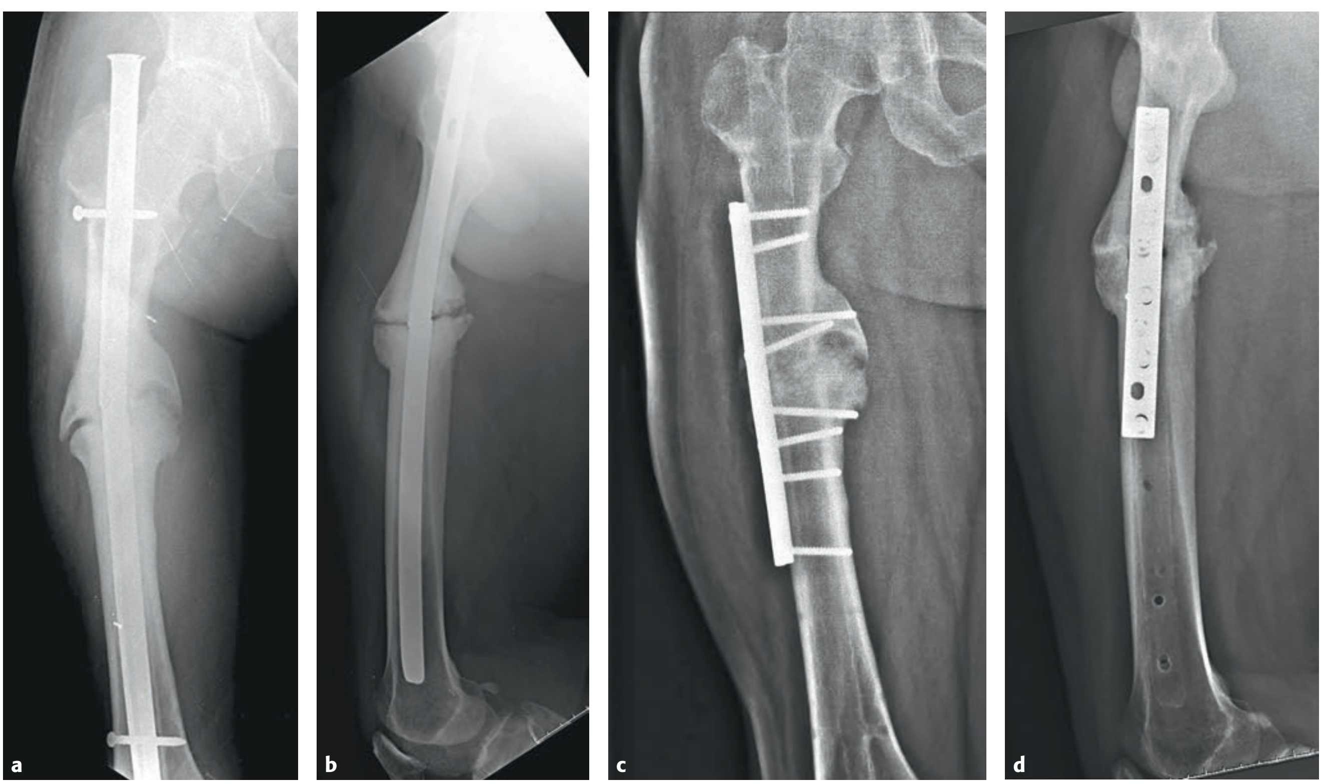


Fig 3.2.3-4a–d Clinical example of a plate acting as a tension band in a nonunion after intramedullary nailing of a femoral nonunion.
a–b Symptomatic nonunion with broken nail—note the hypertrophic area around the fracture site.
c–d After removal of the intramedullary nail, a tension band plate was applied on the lateral or convex side of the femur without bone grafting, and weight bearing was encouraged. The nonunion consolidated.

A tension band that produces compression at the time of application is called a static tension band, as the forces at the fracture site remain fairly constant during movement.

Tension band application to the medial malleolus is an example of a static tension band (**Fig 3.2.3-3d**).

If the compression force increases with motion, the tension band is a dynamic one.

A good example is the application of the tension band principle to a fracture of the patella. Upon knee flexion, the increased tensile force is converted to compression force (**Fig 3.2.3-3a**, **Fig 3.2.3-5**).

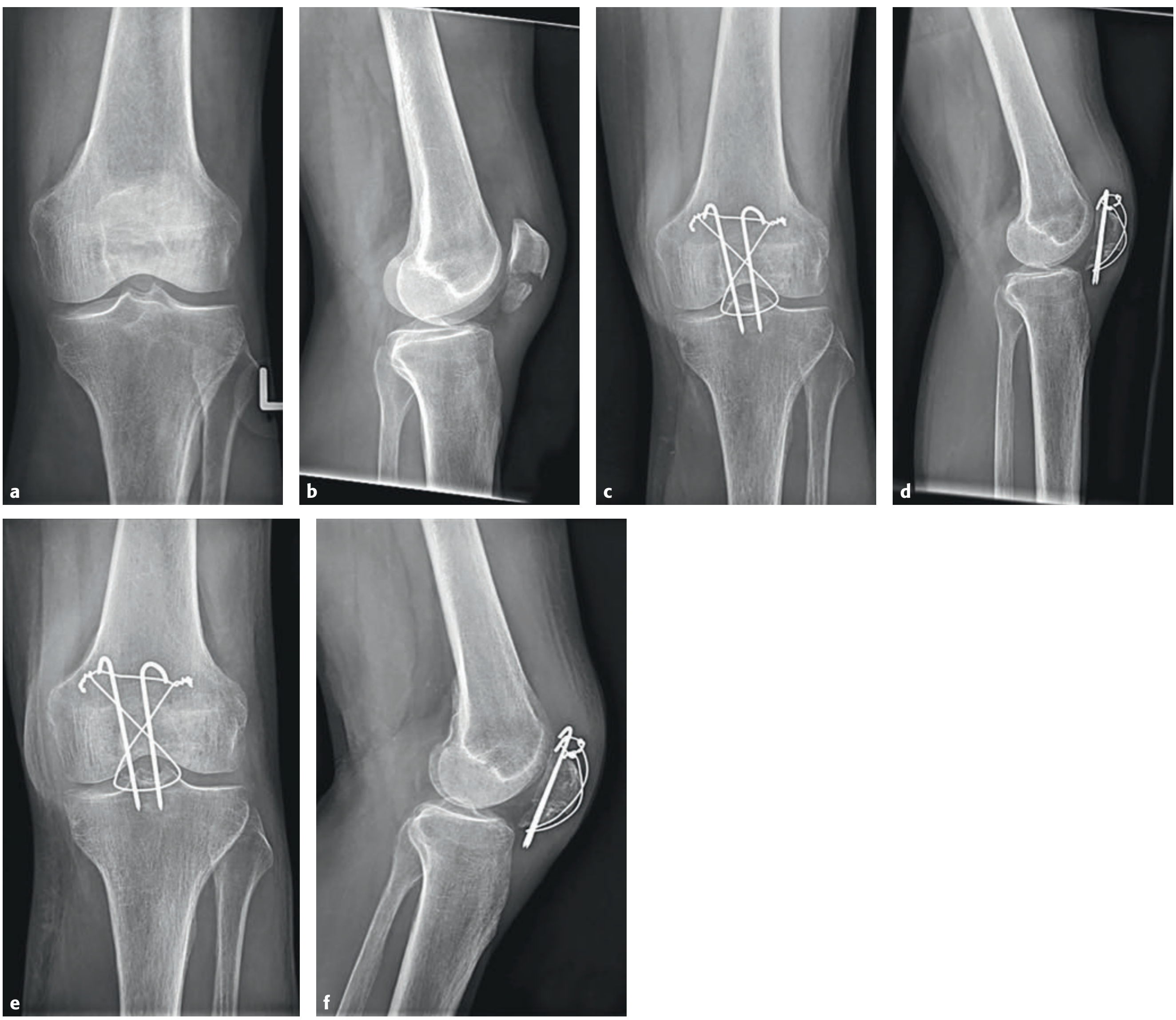


Fig 3.2.3-5a–f A transverse patellar fracture treated successfully with open reduction and internal fixation using a modified tension band technique.

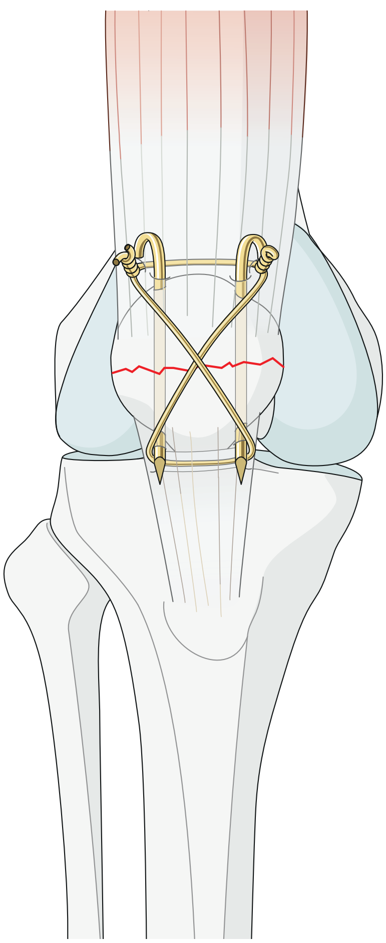
a–b Preoperative AP and lateral views of a transverse patellar fracture amenable to tension band fixation.

c–d Early postoperative views of the tension band construct. Note the placement of K-wires parallel and close to the articular surface. The tension band has been tightened with a double twist to ensure even tension across both sides of the construct.

e–f Late postoperative x-rays demonstrating fracture union. Patient achieved a full return of knee strength and range of motion.

3 Operative technique

Fractures that are subject to distraction forces are at risk of displacement if movement occurs, eg, the patella upon knee flexion or the greater tuberosity of the humerus during contraction of the supraspinatus muscle. By applying a figure-of-eight or a simple loop to the anterior aspect of the patella, and by obtaining good purchase within the insertions of the tendons at either end of the patella, an excellent tension band mechanism is created, which compresses the fracture under dynamic load (**Fig/Animation 3.2.3-6**). The 1.0 or 1.2 mm wire must be anchored as close to the bone as possible. It should be directed through the insertion of the tendons with a large gauge needle (**Fig 3.2.3-3a**). Cannulated screws may also be used in the application of a patellar tension band wire. In this case, two cannulated screws provide interfragmentary compression and a transosseous pathway for the tension band's vertical limbs (**Fig 3.2.3-7**).



Fig/Animation 3.2.3-6 Technique for tension band wiring of the patella. A wire is placed beneath the quadriceps tendon as close to the patella as possible. The wire is crossed in a figure-of-eight fashion across the patella and placed beneath the patellar tendon to complete the tension band. The construct is tightened via simultaneous wire twists on both sides of the patella.

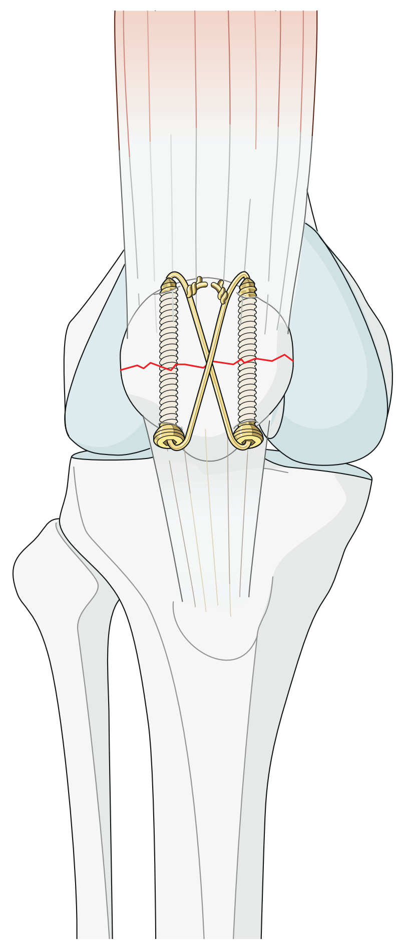


Fig 3.2.3-7 Cannulated screws used in the application of a patellar tension band wire.

In olecranon fractures, the tension band loop is placed through a 2 mm drill hole in the proximal ulna (**Fig 3.2.3-3b**), while in the proximal humerus or medial tibia, a screw head may serve as an anchor (**Fig 3.2.3-3c–d**). A plate or external fixator that functions according to the tension band principle must be applied to the tension side of the bone or the convex side of a deformity or nonunion (**Fig 3.2.3-4**).

The following prerequisites are essential for a tension band fixation:

- Fracture pattern or bone that is able to withstand compression
- Intact cortical buttress opposite to the tension band construct
- Fixation construct that withstands tensile forces

Traditionally, stainless steel wire has been used for tension band fixation; braided metal cables have become popular because of their strength and ease of tightening. The use of nonabsorbable braided polyester suture has been studied and is the mechanical equivalent of 1.25 mm diameter stainless steel wire, with similar healing rates and fewer hardware complications [3, 4]. Biodegradable implants have been applied with success and potentially minimize the complication of painful hardware and decrease the need for implant removal [5]. Nevertheless, biodegradable materials may produce an acute inflammatory soft-tissue reaction that can resemble an infection.

4 Pitfalls and complications

The most common complications are K-wire loosening, prominent hardware, implant failure, and early fracture displacement [6–8].

A wire under tension is strong; however, if bending forces are added, it will break due to fatigue. This principle of fatigue failure also holds true for plates.

In patellar fractures treated with tension band wiring techniques, early fracture displacement has been attributed to nonparallel K-wire placement, poor wire tensioning techniques, and cerclage wires placed too far from the bone to attain solid fixation [9, 10]. These factors allow for fracture displacement with early knee motion. K-wire "back-out" in patellar fixation can be prevented by bending the proximal end posteriorly and impacting it into the proximal cortex of the patella. Tension band wiring through cannulated screws has demonstrated numerous advantages over the modified tension band, including reduced fracture gapping, greater load to failure, and lower hardware removal rates [9, 11].

In simple diaphyseal fractures undergoing plate fixation, the plate should be placed on the tension side of the bone, assuming that the opposite cortex is able to withstand compression forces (**Fig 3.2.3-2c–d**). When the cortex opposite the plate is comminuted, the plate is exposed to repeated bending stress, which invariably will lead to plate breakage if the fracture does not unite rapidly. Early bone grafting may be required to create enough strength to withstand compression forces along the cortex opposite to the plate.

Classic references | Review references

5 References

1. **Pauwels F.** *Biomechanics of the Locomotor Apparatus.* 1st ed. Berlin Heidelberg New York: Springer-Verlag; 1980.
2. **Stoffel K, Klaue K, Perren SM.** Functional load of plates in fracture fixation in vivo and its correlate in bone healing. *Injury.* 2000 May;31 Suppl 2:S-37–50.
3. **Patel VR, Parks BG, Wang Y, et al.** Fixation of patella fractures with braided polyester suture: a biomechanical study. *Injury.* 2000 Jan;31(1):1–6.
4. **Chen C, Huang H, Wu T, et al.** Transosseous suturing of patellar fractures with braided polyester: a prospective cohort with a matched historical control study. *Injury.* 2013 Oct;44(10):1309–1313.
5. **Chen A, Hou C, Bao J, et al.** Comparison of biodegradable and metallic tension-band fixation for patella fractures: 38 patients followed for 2 years. *Acta Orthop Scand.* 1998 Feb;69(1):39–42.
6. **Hung L, Chan K, Chow Y, et al.** Fractured patella: operative treatment using the tension band principle. *Injury.* 1985 Mar; 16(5):343–347.
7. **Kumar G, Mereddy PK, Hakkalamani S, et al.** Implant removal following surgical stabilization of patella fracture. *Orthopedics.* 2010 May;33(5).
8. **Smith S, Cramer K, Karges D, et al.** Early complications in the operative treatment of patella fractures. *J Orthop Trauma.* 1997 Apr;11(3):183–187.
9. **Carpenter J, Kasman R, Patel N, et al.** Biomechanical evaluation of current patella fracture fixation techniques. *J. Orthop Trauma*. 1997 Jul; 11(5): 351–356.
10. **Schneider M, Nowak T, Bastian L, et al.** Tension band wiring in olecranon fractures: the myth of technical simplicity and osteosynthetical perfection. *Int Orthop.* 2014 Apr; 38(4):847–855.
11. **Hoshino C, Tran W, Tiberi III J, et al.** Complications following tension-band fixation of patellar fractures with cannulated screws compared with Kirschner wires. *J Bone Joint Surg.* 2013 Apr 3;95(7):653–659.

6 Acknowledgment

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3.3.1 Intramedullary nailing

Martin H Hessmann

1 Types of intramedullary nails

Intramedullary nailing of shaft fractures of the femur, tibia, and humerus is generally accepted as a standard treatment. Indirect reduction and fixation without opening of the fracture site, implant insertion along the mechanical loading axis of the bone, good bone-implant interface and early load sharing to allow weight bearing are clear advantages of intramedullary nailing. The design and application of intramedullary nails have rapidly evolved since the pioneering work of Küntscher in World War II.

1.1 Classic Küntscher nail (tight fitting, reamed, no locking)

The Küntscher nail was a straight, open section nail with a longitudinal slot and no locking holes. Its use was restricted to relatively simple midshaft fractures because stabilization was dependent upon tight contact between the elastic implant and the stiff bone (intramedullary nailing principle) (**Videos 3.3.1-1–2**). Reaming the medullary cavity increases the area of contact between the intramedullary nail and bone and allows insertion of a larger diameter nail. This extends the indication to fractures that are more complex or more proximal or distal to the isthmus in the shaft. However, the reaming process itself has some inherent biological disadvantages, especially when performed excessively. These include a considerable rise in intramedullary pressure and temperature, increasing the risk of bone necrosis and infection. In the past, these disadvantages limited the use of reamed nailing to fractures with only minor soft-tissue injuries.

1.2 Universal nail (tight fitting, reamed, locked)

The addition of interlocking screws to the intramedullary nail, introduced by Grosse and Kempf, enhanced the mechanical properties of the intramedullary implant. It widened the range of indications to include more proximal or distal fractures, as well as more complex and unstable fracture patterns. However, if the fracture is more distal, more proximal, or more complex, its fixation will mainly depend on the interlocking screws and much less on the principle of circular press fit. The length of the bone-implant construction is still effectively maintained because the interlocking screws prevent shortening and rotation. However, the longitudinal slot in the tubular universal nail results in decreased rotational stiffness and can lead to rotational instability, especially with small diameter intramedullary nails.

Video 3.3.1-1 Küntscher nailing as performed in the middle 20th century.

Video 3.3.1-2 Nail types and mechanics of intramedullary fracture fixation.

1.3 Intramedullary nailing with neither reaming nor locking

Several groups in Europe and North America have treated shaft fractures with significant soft-tissue injuries using solid, small diameter, intramedullary nails, which were inserted without reaming, and therefore, loose fitting. Since these implants (Ender nail, Lottes nail, and Rush pins) were thin and could not be locked proximally or distally, longitudinal and rotational instability resulted, especially in complex fractures. Thus, a major disadvantage was the frequent need for additional external stabilizers, such as plaster casts.

1.4 Intramedullary nailing without reaming but with mandatory locking (unreamed solid or cannulated nails)

There was an obvious need for a small diameter intramedullary nail that could be locked. The absence of a longitudinal slot considerably increases the torsional stiffness of the tubular implant, and also reduces capacity to adapt to the shape of the bone. If the insertion site is not optimal, or the shape and radius of the intramedullary canal diverge from those of the intramedullary nail's geometry, a proper fit may be a problem. With a smaller diameter (ie, 9 mm) in the femur, the material strength of the intramedullary nail must be reinforced to keep the risk of implant failure as low as possible. These two demands (low stiffness and high-fatigue strength) were met by a change of material, from stainless steel to a titanium alloy. Titanium nails seem to have a beneficial effect on strength, mineralization, and fracture healing at 12 weeks [1]. The higher strength of the material allows the use of larger, 4.2/4.9 mm diameter interlocking screws. The solid cross-section of the intramedullary nail does not add much to its mechanical bending properties, but it has biological advantages. Results of animal experiments indicate that the susceptibility to infection is lower with the solid intramedullary nail compared with the tubular intramedullary nail with its inner dead space [2]. However, a cannulated system allows for the use of a guide wire, which makes intramedullary nail insertion easier.

1.5 Angular stable locking system (ASLS)

Intramedullary nails with standard locking options provide adequate stability in long-bone shaft fractures. In metaphyseal and segmental fractures, however, the wide diameter of the medullary canal and fracture morphology may cause problems with reduction and stable fixation of the short proximal or short distal fragment because circular press fit of the implant in the wide medullary cavity cannot be obtained. Malunion and/or nonunion are common. The improved 3-D design of proximal and distal locking has expanded the spectrum of indications of intramedullary nailing to metaphyseal and even simple articular fractures of the femur, tibia, and humerus [3]. These implants are cannulated and the instrumentation is modular. Relative movement of the main fragments is effectively reduced by angular stable locking screws. Angular stability is produced by a mechanical couple between the locking screws and the nail. This can be achieved by jamming locking screws or by the use of resorbable sleeves inserted into the locking holes of the nail (ASLS) [4].

2 Pathophysiology of intramedullary nailing

2.1 Intramedullary nailing with reaming

2.1.1 Local response

Reaming the medullary cavity causes damage to the internal cortical arterial and venous blood supply, which, in animal experiments, was shown to be reversible within 8–12 weeks [5]. There is a direct correlation between the extent of reaming and the degree of the reduction in cortical blood flow. Reaming also generates heat and may cause thermal bone necrosis. Large reamers and blunt reaming heads should not be used in clinical practice. The reduced blood supply and thermal bone damage during the early weeks after trauma and reaming might contribute to an increased risk of infection, especially in open tibial fractures. Since the femur has a good soft-tissue envelope, femoral shaft fractures are more often closed than open and treatment by intramedullary nailing is more straightforward and less risky than for the tibia. The infection rates for Gustilo type I and type II open fractures of the femur following intramedullary nailing with reaming are 1–2%, whereas for open fractures with extensive soft-tissue injury (Gustilo type III) the infection rates are 4–5%.

There are some biological advantages of intramedullary reaming, as it enhances the bone healing process by:

- Increased perfusion and oxygenation in the adjacent soft tissues
- Reaming debris has osteogenic and osteoinductive properties
- Local "autografting" of bone debris into the fracture site stimulates osteogenesis
- Systemic liberation of growth factors
- Allowing the insertion of larger (mechanically more stable) diameter nail

Clinical studies [7] demonstrate a possible benefit for reamed intramedullary nailing in patients with closed fractures, whereas the optimal nailing technique for open fractures remains uncertain.

2.1.2 Systemic response

Systemic effects of intramedullary reaming are pulmonary embolization, humoral, neural, immunological, and inflammatory reactions plus temperature-related changes of the coagulation system. Intramedullary pressures exceeding the diastolic blood pressure result in extravasation of bone marrow content into the venous vascular system (fat embolism). Transesophageal echocardiography (TEE) shows the passage of thrombi into the pulmonary circulation. Pulmonary embolization may cause mechanical vascular obstruction. Systemic liberated fatty acids and bone debris additionally induce vasculitis of vessels within the lung [8]. Liberation of inflammatory mediators, such as thromboxane, serotonin and prostaglandins, cause bronchial spasms and vasoconstriction. Due to shunt systems within the lung, fat embolism may also get access to the systemic circulation, evoking cerebral embolization.

Any device introduced into the medullary canal (awl, guide wire, reamer, intramedullary nail) acts as a piston and forces the contents of the medullary cavity both through the fracture gap into the adjacent tissue and into the venous system. Polytrauma patients with chest injury are especially at risk, since the lungs are sensitive to any additional stress in the period immediately after trauma.

Distal venting of the femur has been shown to reduce the intramedullary pressure during reaming by 50–90%. The clinical efficacy of this technique, however, has not been documented in prospective randomized trials.

There is ongoing controversy between those who recommend reamed intramedullary nailing for all patients with severe trauma, and those with concerns about its role in pulmonary impairment in multiple-injured patients [9]. Recent clinical studies [10] found similar rates of pulmonary embolism and no significant difference in the rate of pulmonary response between reamed and unreamed femoral nailing, provided surgery was delayed until the patient was fully resuscitated (early appropriate care). Comparing reamed femoral nailing with plate fixation in multiple-injured patients with head injury showed that nailing did not increase the risk of neurological complications [11].

2.1.3 Reaming, irrigation, and aspiration

The reaming, irrigation, and aspiration (RIA) system was developed to reduce the amount of systemic fat liberation during the procedure of reaming [12]. Irrigation during the reaming procedure reduces the viscosity of the bone marrow and allows suction of the intramedullary content. Reaming using the RIA technique lowers the maximum reaming temperature and causes less sustained increases in intramedullary pressures in comparison to conventional reaming [8]. A significant reduction of fat embolization compared to conventional reaming could be demonstrated in pig femora [12]. However, values were still higher than with external fixation. Whether RIA reduces systemic complications during nailing of femoral fractures in multiple-injured patients still needs further investigation.

Reaming, irrigation, and aspiration are also used for nailing of pathological fractures and for debridement in patients with acute and chronic osteomyelitis. An additional application of RIA is bone harvesting by sucking the reaming eluate through a filter for surgical procedures, such as treatment of bone defects and nonunions. Similar union rates with significant less donor-site pain in comparison to iliac crest harvesting have been reported [13]. However, extensive thinning of the inner cortex of more than 2 mm may be a risk factor for postoperative fracture of the donor site and the surgical and anesthetic teams must be aware that this procedure can result in considerable blood loss.

2.2 Intramedullary nailing without reaming

Small diameter implants are used for intramedullary nail insertion without reaming. The benefits are less heat production, and, although the insertion of thinner implants certainly disturbs the endosteal blood supply, this occurs to a lesser extent. There is also less bone necrosis, which is one of the risk factors for the development of postoperative infection. However, an explicit clinical benefit of unreamed intramedullary nailing in comparison to reamed nailing has not be demonstrated.

A metaanalysis comparing reamed versus unreamed nailing in closed fractures of the tibia showed a significantly lower risk of nonunion, screw breakage, and implant exchange in the reamed nailing group [14]. Reamed nailing of closed fractures seems to be associated with a higher fracture healing [7, 8].

2.3 Current aspects of femoral intramedullary nailing

2.3.1 Isolated femoral shaft fractures

Both methods of intramedullary nailing (reaming and not reaming) are associated with similar generation of emboli. A prospective, randomized, clinical study [15] found no significant differences in pulmonary physiological response or clinical outcome between patients treated with unreamed or reamed femoral nailing.

Other clinical studies have demonstrated significant benefits of reaming compared to unreamed femoral nailing. In a multicenter, prospective, randomized trial [16], intramedullary nailing of femoral shaft fractures without reaming resulted in a significantly higher rate of nonunion compared to intramedullary nailing with reaming. In addition, reaming led to faster healing and a reduced rate of delayed union.

Femoral nailing with reaming remains the gold standard for the treatment of isolated femoral fractures.

2.3.2. Femoral shaft fractures in polytrauma patients

In multiple-injured patients, especially in the presence of chest trauma, the reamed femoral nail has been implicated as a cause of significant disturbance of pulmonary function. Using an unreamed nail reduces but does not abolish pulmonary sequelae. In addition to the pulmonary consequences of intramedullary nailing, systemic effects on the coagulation system and on the inflammatory response with increased levels of interleukin-6 and C-reactive protein have been reported in clinical and experimental studies for both the reamed and the unreamed femoral nail [17]. No significant differences in the incidence of acute respiratory distress syndrome (ARDS) were observed following reamed and unreamed nailing in a series of 315 multiple-injured patients with femoral fractures, treated with a nail within 24 hours after injury [18].

To limit the physiological insult resulting from operative treatment after trauma, a move from early total care (ETC) to damage-control orthopedics (DCO) in patients with multiple injuries has occurred. Damage-control orthopedics starts with initial external fixation of femoral shaft fractures with a later conversion to an intramedullary nail [19]. This concept has been judged as a viable alternative to obtain temporary fracture stabilization in polytrauma patients, especially those with concomitant injuries to the head, chest, or an exceptionally high injury severity score (ISS) [17, 20].

Definitive primary femoral stabilization by intramedullary nailing imposes considerable stress on a multiple-injured patient with blunt trauma. Principles of management include adequate resuscitation with appropriate timing of reconstruction depending on the patient's physiological response.

Vallier et al [10] defined clinical conditions that warranted delay for definitive fracture fixation in a retrospective study on 1442 patients with pelvic, spinal, and/or femoral shaft fractures. Chest injury was identified as the greatest predictor of pulmonary complications. The authors emphasized the importance of adequate resuscitation and correction of acidosis before nailing. They recommended early definitive fixation of unstable fractures of the axial skeleton and long bones within 36 hours in patients who demonstrated response to resuscitation. Lactate < 4.0 mmol/L, pH > 7.25, and BE > 5.5 mmol/L were indicators to proceed with definitive fracture fixation.

Pape et al [21] described four pathophysiological cascades, associated with the development of posttraumatic immune dysfunction and endothelial damage. They recommended assessing for hemorrhagic shock, hypothermia, coagulopathy, and soft-tissue injury in all patients with multiple blunt trauma and long-bone fractures. Clinical parameters that characterize an unstable patient (as opposed to a stable or a borderline patient) include blood pressure < 90 mm Hg, body temperature < 33° C, platelets < 90,000, and significant soft-tissue trauma (major extremity injuries, crush trauma, severe pelvic fracture, thoracic and abdominal trauma with AIS > 2).

Even when the initial insult of trauma (the "first hit") is moderate, a "second hit" resulting from surgical procedures with inappropriate timing can aggravate the overall amount of damage and may lead to an increased morbidity and mortality [9]. Pape et al [21] suggested categorizing patients into one of four categories (stable, borderline, unstable, in extremis) and adapting the treatment approach accordingly. In patients who are unstable or in extremis, damage-control surgery, including rapid external fixation of long-bone fractures, followed by early secondary definitive fracture stabilization, typically within 5–7 days, is recommended.

In patients with delayed definitive fracture fixation (> 2 weeks), or if there is pin-site infection, converting provisional external fixation to intramedullary nailing should include a short fixator-free interval (pin holiday) [19] of 2–3 days, during which patients are placed in skeletal traction to reduce the risk of infection.

2.4 Current aspects of tibial intramedullary nailing

Intramedullary nails are the treatment of choice for most unstable tibial diaphyseal fractures. The incidence of intravasation of intramedullary content and pulmonary embolization after tibial fractures is significantly lower than after femoral shaft fractures (tibia 19% versus femur 78%) as the venous drainage system of the tibia is less extensive than that of the femur.

The use of intramedullary nails with reaming for the treatment of closed tibial fractures results in shorter time to union without an increase of postoperative complications [22]. A higher rate of malunions after unreamed intramedullary nailing has been reported than after reamed intramedullary nailing [22]. A reamed procedure for stabilization of the tibia did not increase the risk of complications in open tibial fractures of the Gustilo type I–IIIA [22].

The SPRINT blinded randomized trial [7] compared healing rates and complications after reamed and unreamed intramedullary nailing of open and closed tibial fractures in a large series of 1,319 adults. The study demonstrated a possible benefit for reamed nailing in closed fractures with fewer screw breakages, whereas there were no significant differences between both procedures in patients with open fractures. The reoperation rate in response to infection was not significantly different between both groups [7].

2.5 Conclusion

The systemic impact of intramedullary nailing of femoral shaft fractures seems to be significantly higher compared to tibial fractures. There is good evidence that reamed femoral intramedullary nailing is the method of choice for isolated femoral shaft fractures. In polytrauma patients, adequate resuscitation before nailing is essential. Early definitive intramedullary stabilization of the femur should not be performed in patients in extremis or who do not respond to resuscitation and continue to have uncorrected acidosis, coagulopathy, or severe hypothermia. The preferred approach is damage-control surgery with temporizing external fixation.

Stabilization of tibial fractures is mostly influenced by local soft-tissue factors. For closed tibial fractures, reamed intramedullary nailing is the method of choice. In open fractures the method of choice remains controversial.

3 Implants

3.1 Femur

The universal femoral nail is a curved, slotted intramedullary nail made of stainless steel and is still widely used in many parts of the world. It has a static and dynamic locking option proximally, and two static locking options distally. The femoral version of the simplified universal nail (SUN) is an unslotted, tubular version of the universal femoral nail. Both the SUN and the SIGN nail have been designed for hospitals without an image intensifier, with a simple mechanical aiming device to allow for interlocking without image guidance.

The unreamed femoral nail is a solid titanium nail with a variety of proximal locking options (static, dynamic, spiral blade, and miss-a-nail). It is curved and requires an entry point in line with the medullary cavity. The cannulated femoral nail allows the insertion along a guide wire. The entry point in the piriformis fossa has been criticized for being technically demanding, with a possible risk of compromising the blood supply to the femoral head. This led to the development of the antegrade femoral nail, which has a bend in the proximal part that allows for insertion at the tip of the greater trochanter. The lateral femoral nail has a starting point even more lateral to the tip of the greater trochanter. The very lateral starting point facilitates nail insertion. The nail has a helical design and rotates by approximately 90° during insertion. Standard and reconstruction locking options provide stability in diaphyseal as well as in subtrochanteric and segmental fractures. The adolescent femoral nail is used in small stature (adolescent) patients with small diameters of the medullary cavity.

The distal femoral nail is specifically designed for retrograde insertion. The proximal locking is performed anteriorly in long nails and lateral to medial in short nails. As part of the expert nail system the retrograde/antegrade femoral nail can be introduced through an antegrade as well as a retrograde entry point. It is cannulated and allows for optional spiral blade locking at the level of insertion with retrograde insertion.

For fractures in the proximal femur (subtrochanteric or intertrochanteric), intramedullary nail-screw combinations are available in different dimensions for different indications. The original proximal femoral nail with two parallel femoral head screws of different sizes has mainly been used outside the US, while in the US the trochanteric femoral nail is popular. The trochanteric femoral nail has a double spiral blade configuration for improved rotational stability in the femoral head/neck area. This design has now been integrated into the proximal femoral nail, resulting in the proximal femoral nail antirotation. Both the proximal femoral nail antirotation and the proximally smaller sized trochanteric femoral nail-advanced can be used with either a blade or a head-neck screw. Perforations at the tip of the blade or screw allow for cement augmentation that aims to reduce failure rates in osteoporotic bone by increasing the implant to bone surface contact area.

Every specific nail has its own specific entry point. Each specific entry point has advantages and potential complications. The piriformis starting point, which is collinear with the axis of the femoral medullary canal, is appropriate for nails that are straight in the AP plane (eg, unreamed femoral nail). Piriformis start nails are better for preventing varus deformity and offer excellent stability specifically in subtrochanteric fractures. Occasional femoral neck fractures have been described after nailing through the piriformis fossa. Concern exists in young patients with an open proximal femoral growth plate about the potential risk of avascular necrosis, resulting from intraoperative damage to the medial circumflex femoral artery [23].

Nails with a lateral bend have a more lateral starting point, usually at or just lateral to the tip of the greater trochanter. Inserting a nail through a lateral entry point is mechanically stable, technically easier to perform and causes less damage to the muscles and vascular structures [24].

Reamers for nails inserted into the tip of trochanter tend to lateralize the center of the entry point as the lateral bone is softer. This can result in varus malalignment when the nail is inserted and these nails must be used with caution for subtrochanteric fractures.

In a prospective randomized trial, Stannard et al [25] compared functional outcome with the piriformis fossa and the greater trochanter entry point in the treatment of femoral shaft fractures. The tip of the trochanter starting point resulted in a better outcome at 6 months but function was equal at 1 year. Pain scale values were equal in both groups [25]. From the technical perspective, operative time and image intensifier time were significantly shorter and incision length was smaller with the trochanter starting point, indicating that nailing through the tip of trochanter entry is a simpler procedure.

3.2 Tibia

The universal tibial nail is a slotted tubular intramedullary nail made of stainless steel, which is still widely used in many parts of the world. It has a static and dynamic locking option proximally, and two static locking options distally. There is a SUN for the tibia which is an unslotted, hollow version of the universal tibial nail. The SUN nail as well as the SIGN nail is designed for hospitals where an image intensifier is not available, with a simple mechanical target device to allow for interlocking without radiation. The unreamed tibial nail is a solid titanium nail with a variety of proximal locking options (oblique, dynamic, static). The cannulated tibial nail allows for insertion along a guide wire. The expert tibial nail system offers additional and improved proximal and distal locking options with a 3-D configuration, which makes this nail suitable for the fixation of proximal and distal metaphyseal fractures as well as for segmental fractures.

3.3 Humerus

The unreamed humeral nail is a locking intramedullary nail, which provides the smallest diameter (6.9 mm) and the use of a spiral blade into the humeral head. The proximal bend allows for antegrade and retrograde insertion. The proximal humeral nail is a short unreamed humeral nail, specifically designed for proximal humeral fractures. The expert humeral nail is cannulated and has the option for either antegrade or retrograde insertion. Newer humeral nails with multi-locking options are available in a short and a long version with 3-D angle-stable locking possibilities and the option of inserting secondary screws (screw-in-screw technique) to enhance the stability of proximal fixation. The nail is appropriate for both simple type A as well as complex types B and C fractures [26]. As the implant is straight, it is inserted in the axis of the humerus and the proximal end of the nail acts as a fifth anchor point in addition to the four locking screws. In its long version, the nail allows optional compression; it is appropriate for the fixation of both diaphyseal and segmental fractures.

3.4 Forearm

Intramedullary fixation of forearm shaft fractures is limited to the titanium elastic nail. It has only exceptional indications in adults because rotation around the nail cannot be prevented. Locked nailing systems for the forearm are in development. The short olecranon nail is mainly used for surgical fixation of osteotomies of the olecranon as well as for simple articular fractures of the proximal ulna.

3.5 Clavicle

Simple midshaft fractures of the clavicle are—as an alternative to plate fixation—successfully addressed by elastic stable intramedullary nailing. Elastic titanium nails with a diameter of 2.0–3.0 mm are inserted from medial to lateral. Fracture reduction is achieved either in a closed or minimally open manner. The use of elastic stable intramedullary nailing in comminuted fractures is still being debated, since the technique may be associated with complications like shortening, telescoping, and skin perforation [27].

3.6 Lateral malleolus

Locking nails have been developed for fixation of lateral malleolar fractures in patients with osteoporosis or multifragmentary fractures with the option of placing a diastasis screw (see chapter 6.9).

4 General techniques

4.1 Preoperative planning and management

4.1.1 Patient positioning

The traction table or a standard radiolucent operating table, with or without the use of the femoral distractor, are alternatives for patient positioning for femoral nailing. Nailing can be done either in the lateral or in the supine position. The use of a traction table will maintain defined reduction throughout the procedure, which may be helpful in the placement of reamed intramedullary nails. Much depends on personal experience and preference as well as on the operating room environment. With the unreamed intramedullary nail, maintenance of accurate reduction is only necessary for the short period required to pass the intramedullary nail from the proximal fragment into the distal main fragment. In reamed intramedullary nailing, however, preservation of fracture reduction is a requirement for every passage of the reamer and, finally, for the insertion of the nail as well. Polytrauma patients with ipsilateral and/or bilateral tibial and/or femoral fractures can be treated on a regular operating room table without the need to change either the position of the patient or the drapes. This appears to be safer and quicker. Intraoperative control of rotational alignment is easier when both legs are draped.

4.1.2 Sequence of stabilization in multiple extremity fractures

The recommended order for the treatment of closed fractures is:

1. Femur
2. Tibia
3. Pelvis or spine
4. Upper limb

To follow this sequence, alternative methods were developed for the treatment of concomitant ipsilateral and/or bilateral fractures of the lower limb. In multiple fractures of the lower limb, standardized stabilization protocols have been helpful for the sequence and method of stabilization according to the patient's condition (stable, borderline, unstable, in extremis). More recent techniques for intramedullary stabilization are no longer based on a fracture table but show a preference for the temporary use of a distractor or manual traction. This allows a single positioning and draping procedure for stabilization of multiple fractures.

4.1.3 Correct implant selection

Preoperative selection of intramedullary nail length

Templates are commonly recommended for the preoperative planning of intramedullary nailing. The accuracy of templates, however, is dependent upon the x-ray magnification. Unfortunately, there is currently no accepted standard for long bones, and magnification ranges from 10–20%. As a consequence, templates are highly unreliable for selecting the correct nail length. Implant selection should be based on an x-ray of the intact contralateral bone, intraoperative clinical measurements, or image intensifier-based measurements with the use of opaque rulers. Clinical comparison with the uninjured limb is another reliable option but requires separate draping of the uninjured leg.

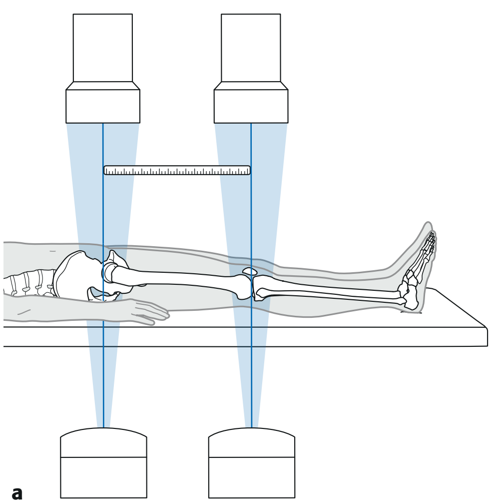
Measuring intramedullary nail length intraoperatively with a special ruler under C-arm control is an accurate method for implant selection. If the proximal and distal ends of the bone are centered in the x-ray beam, and the ruler is placed parallel to the diaphysis, projection-induced misjudgment of implant length is minimized (**Fig 3.3.1-1**).

An alternative manner of selecting intramedullary nail length is to draw the landmarks onto the skin using a sterile pen and measure with a ruler. The proximal landmark in the femur is the tip of the greater trochanter, which is identified by palpation. The distal landmarks are the lateral knee joint space and/or the superior edge of the patella. In simple fracture patterns, one picture of the reduced fracture site taken with the image intensifier allows correct measurement and choice of an intramedullary nail of appropriate length.

Proximal landmarks for the tibia are both the medial and lateral knee joint spaces; the distal point is the anterior part of the ankle joint with a dorsally flexed foot.

Selecting the intramedullary nail diameter

A special ruler permits measurement of the implant diameter (**Video 3.3.1-3**). A technical trick for the selection of the cavity diameter during intramedullary nailing is the use of the reamer head as a probe.



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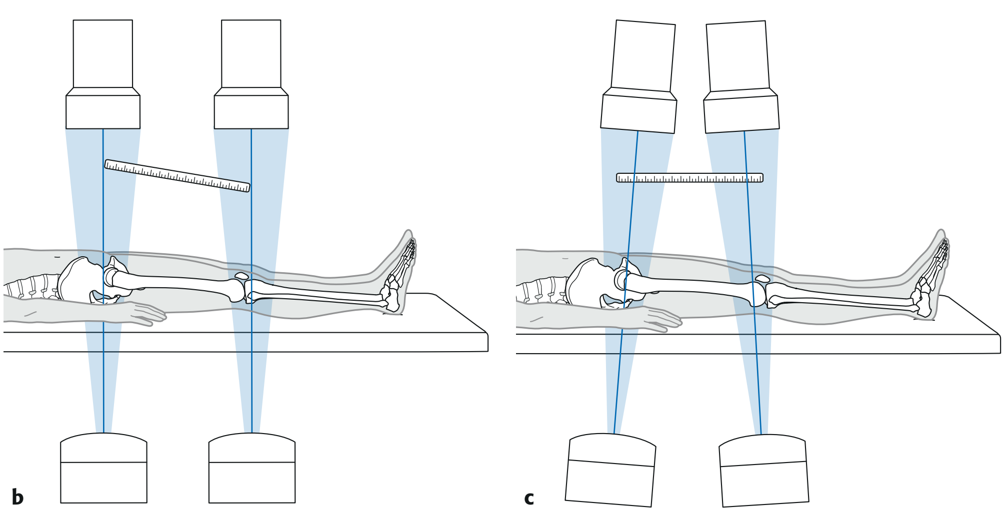


b

c

Fig 3.3.1-1a–c Intraoperative determination of nail length with the use of an image intensifier. Note that errors can occur in various combinations to produce different patterns of error.

- **a** Correct position of patient, C-arm, and ruler parallel to the femur.
- **b** Error: Nonparallel ruler position results in too long a measurement.
- **c** Error: Eccentric position of the C-arm results in too short a measurement.

Video 3.3.1-3 Preoperative planning of nail length and diameter in the femur with a special ruler.

4.2 Insertion techniques

4.2.1 Surgical approach and preparation of the entry point

Stab incision techniques have been developed for the femur and the tibia. In both bones, care must be taken to place the incisions in line with the axis of the medullary cavity and not too close to the chosen entry point on the bone (**Figs 3.3.1-2–3**). Smaller approaches reduce blood loss as well as the risk of heterotopic ossification at the tip of the greater trochanter of the femur.

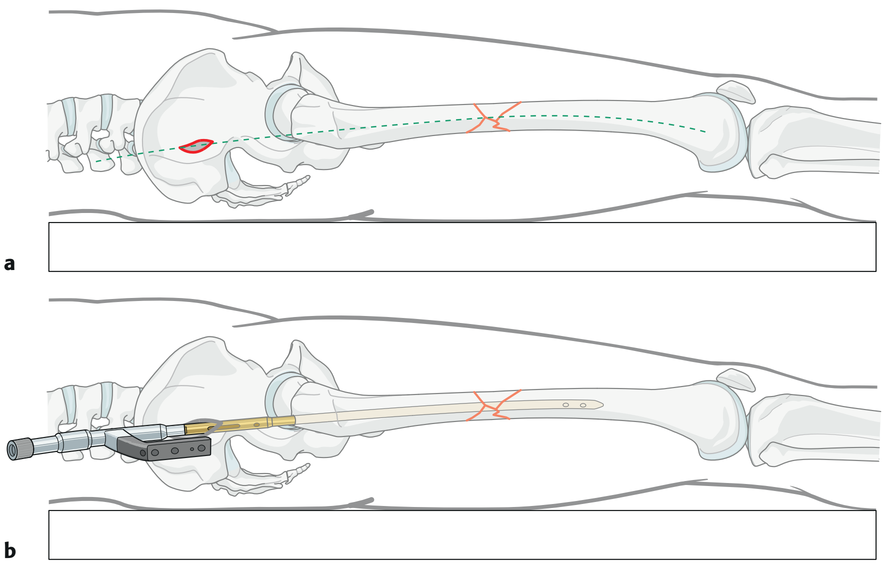


Fig 3.3.1-2a–b Surgical approach for antegrade femoral nailing. When planning the stab incision, which lies approximately 10 cm proximal to the tip of the greater trochanter, the natural antecurvation of the femur has to be considered. Before making the incision it is useful to identify it using the image intensifier and a metal ruler and mark the position of key anatomical landmarks with a skin marker pen.

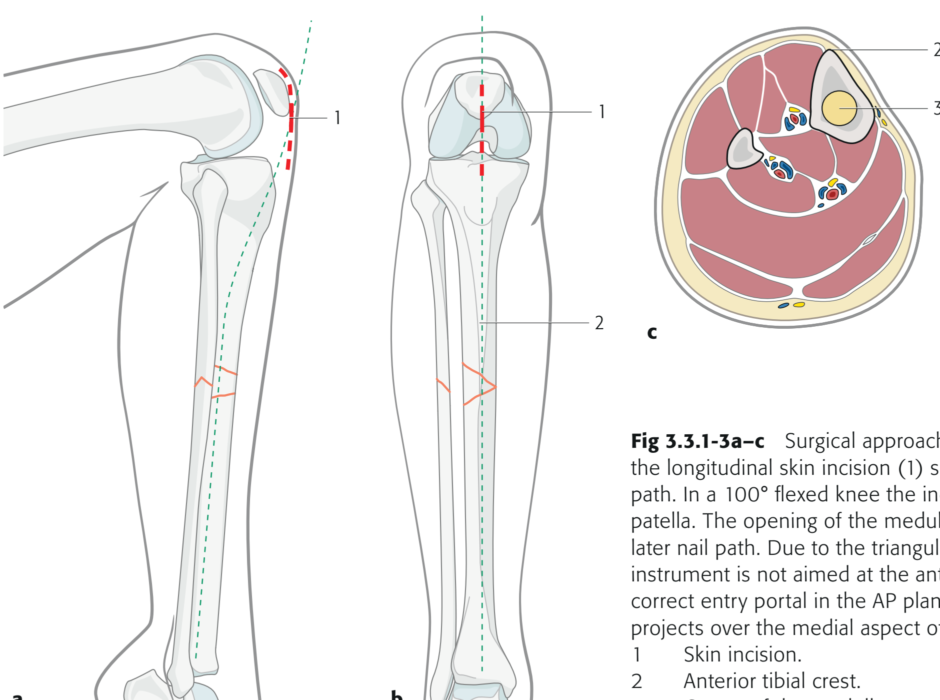


Fig 3.3.1-3a–c Surgical approach for intramedullary nailing of the tibia: the longitudinal skin incision (1) should be in line with the chosen nail path. In a 100° flexed knee the incision lies over the lower end of the patella. The opening of the medullary cavity should also be in line with the later nail path. Due to the triangular cross-section of the tibia, the opening instrument is not aimed at the anterior tibial crest (2) but medial to it. The correct entry portal in the AP plane is slightly lateral from the midline and projects over the medial aspect of the lateral eminentia.

1 Skin incision.
2 Anterior tibial crest.
3 Center of the medullary canal.

4.2.2 Preparation of the entry point in antegrade femoral nailing

The correct entry point is crucial in all intramedullary nailing. A suboptimal entry point leads to malalignment and may create iatrogenic fractures during implant insertion.

The surgeon should always view the entry point on the AP and lateral image before opening the bone.

In the femur, flexion and adduction of the hip joint facilitates the approach to the trochanter for antegrade femoral nailing. This decreases the length of the incision, especially in obese patients. The greater trochanter, lateral femoral condyle, and, if possible, the femoral shaft are palpated and, if necessary, identified with a marker. A line is drawn in a proximal direction corresponding to the curvature of the femur. A stab incision of about 3–5 cm is made approximately 10 cm proximal to the tip and directed toward the greater trochanter (**Fig 3.3.1-2**). This allows insertion of a palpating finger alongside the implant (**Video 3.3.1-4**). Incisions should not be placed too posteriorly since abductor muscle weakness has been recorded after intramedullary nailing. The choice of the correct entry point is crucial and the surgeon must be aware that there is considerable variation in normal anatomy [28]. Too posterior with the starting point may lead to loss of reduction; too anterior with the entry point generates huge forces and may lead to bursting of the proximal femur. Depending on the intramedullary nail design, different entry points are recommended (piriformis fossa, tip of the greater trochanter, etc). This must be considered in every case (**Fig 3.3.1-4**).

Video 3.3.1-4 Clinical video of the surgical approach for antegrade femoral nailing.

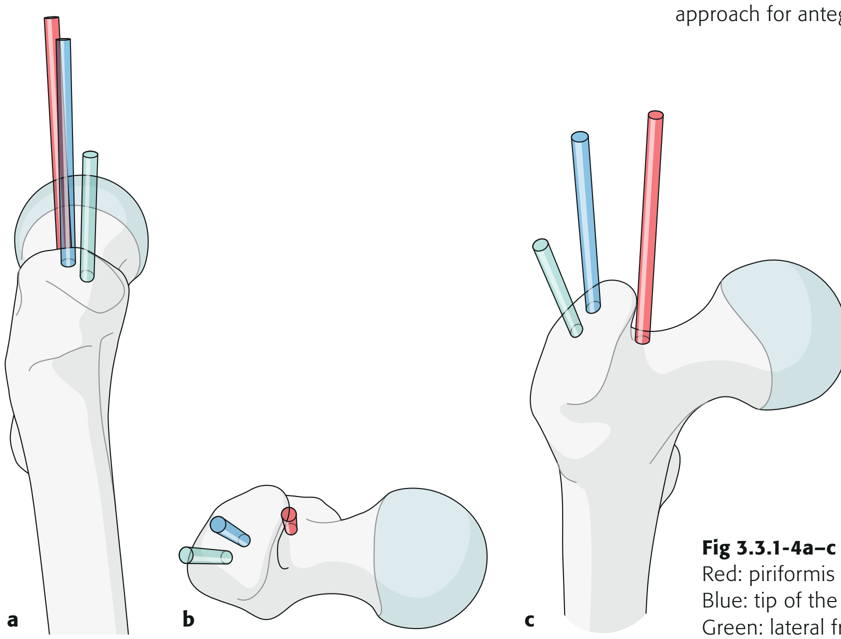


Fig 3.3.1-4a–c Correct entry points for various nails.
Red: piriformis or trochanteric fossa.
Blue: tip of the greater trochanter.
Green: lateral from the greater trochanter.

The perfect position of the guide wire in both planes is rarely achieved on the first attempt, especially in the femur. In these cases, a correct second pin is inserted using the initial wire as a reference. A multi-hole wire guide is a useful instrument that allows insertion of a second guide wire in corrected position. A sleeve protects the hip abductors from the 3.0 mm cannulated drill bit used to open the entry point.

4.2.3 Preparation of the entry point in retrograde femoral nailing

For retrograde nailing of the femur, the knee is flexed approximately 30°. A guide wire is lined up with the midline of the medullary cavity of the distal femoral shaft, using an image intensifier. The stab incision is placed on this line and a K-wire with a protection sleeve is pushed through or just medial to the ligamentum patellae into the distal femur. The position of the K-wire is also checked in a lateral view. Care must be taken that the origin of the posterior cruciate ligament is not injured. The important landmark in the lateral view is the Blumensaat line, a radiodense line representing the cortical bone of the roof of the intercondylar notch of the femur.

4.2.4 Antegrade tibial nailing

In the tibia, with the knee completely flexed, a 15–20 mm stab incision is made in line with the medullary cavity. The incision starts at the inferior pole of the patella and passes through the patellar tendon (or just medial to it) and all layers down to the bone (**Fig 3.3.1-3**). The proximal anterior edge of the tibia can be easily identified with the sharp tip of the guide wire.

The 4.0 mm guide wire, mounted on a universal chuck with T-handle, is pushed through the thin cortex in the direction of the center of the medullary canal. The position is checked with an image intensifier with both AP and lateral views. Accurate position is important (see chapter 6.8.2). The protection sleeve for the cannulated cutter is placed through the stab incision and through the patellar ligament directly onto the bone. The cannulated cutter ("cheese cutter") for the medullary canal cuts out a cylinder of corticocancellous bone. This may be used as bone graft. To prevent malalignment it is essential to place the entry point exactly in line with the center of the medullary cavity.

Alternatives to the transtendinous patellar approach are the medial parapatellar approach and the suprapatellar approach. The suprapatellar approach has the great advantage that nailing can be done in a semiextended position, which is especially beneficial in fractures of the proximal tibia and in segmental fractures (**Video 3.3.1-5**). The stable position of the lower leg and less deforming force from the patellar tendon facilitates fracture reduction and instrumentation. To avoid damage to the cartilage of the knee, it is mandatory to use a soft protection sleeve while passing instruments and implants through the joint [29].

4.2.5 Floating knee injury

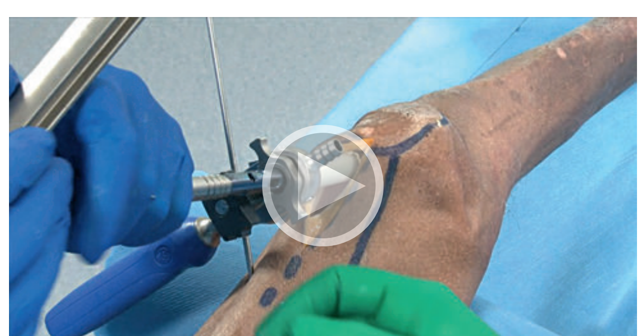
In cases where retrograde femoral and antegrade tibial nailing is planned, intramedullary nail insertion can be performed through the same skin incision. In this situation the surgeon must ensure that the incision is proximal enough to allow insertion of the retrograde nail (close to the patella).

4.2.6 Reaming technique

For fresh fractures, power reamers are more convenient and faster than hand reamers. However, for more difficult situations (eg, nonunions with sclerosis of the medullary cavity), specially designed hand reamers are safer and more effective. Reamer design and condition (cutting flutes, geometry and diameter of the reamer shaft, sharpness, etc) are important.

> Blunt reamers, small flutes, high axial forces, and large diameters of the reamer shaft cause an increase in pressure and temperature.

Cases of thermal necrosis of the femur and tibial isthmus after reaming have been observed. The temperature rise is mainly related to the amount of reaming performed on hard cortical bone. Some surgeons recommend that a tourniquet is not used when reaming the tibia but a randomized trial suggests that this may be an acceptable technique [30].



Video 3.3.1-5 Suprapatellar approach for antegrade tibial nailing.

The use of a distal venting hole to reduce intramedullary pressure during reaming is dependent on the diameter of the hole. This method is not generally used for fractures but a distal venting hole is essential if an intact bone is reamed for prophylactic nailing of an impending pathological fracture.

4.3 Reduction techniques

4.3.1 Reduction of femoral fractures

For several reasons femoral fractures are more difficult to reduce than tibial fractures:

- Thicker soft-tissue envelope and less direct access to bone.
- More deforming muscle force.
- Entry point at the proximal end is partly hidden.
- Iliotibial tract tends to shorten the fracture if the leg is adducted.

4.3.2 Reduction of tibial fractures

The most effective and gentle instruments for reducing fresh tibial fractures are our hands. In contrast to the femur, large parts of the tibia are easily palpated. Since most fractures are type A or B fractures of the midshaft or distal diaphysis, they are suitable for simple manual reduction during implant insertion. Temporary overcorrection of the fracture zone during intramedullary nail passage is sometimes advantageous and helpful in oblique fractures.

4.3.3 Reduction aids

Reduction of fresh fractures for closed intramedullary nailing is rarely a problem but delayed intramedullary nailing often requires additional tools to overcome shortening and to control axial alignment. The traction table is safe and reproducible for some surgeons but some prefer the limb free on a radiolucent table.

The towel-sling and beanbag techniques are easy, noninvasive, and inexpensive ways of manipulating the main fragments. However, they are rather imprecise and not suitable for adjusting the length. In the tibia, pointed reduction forceps are best used, since they can be applied percutaneously or through an open wound, without additional soft-tissue trauma.

The use of temporary Schanz screws is an effective way to get direct contact with the bone. This is especially helpful in femoral or delayed tibial fractures. Three principles have to be respected:

- Screw placement must be as close to the fracture as possible.
- Monocortical insertion is used in the proximal fragment in order not to interfere with implant insertion.
- A universal chuck with T-handle is used for easier manipulation.

There are two planes in which reduction has to be controlled:

- Coronal (AP) plane
- Sagittal (lateral) plane

Use of the image intensifier can be reduced by fixing universal chucks with T-handle to the Schanz screws and analyzing their position in relation to each other. Furthermore, tactile control of the main fragments may also decrease the need for radiation exposure (**Fig 3.3.1-5**).

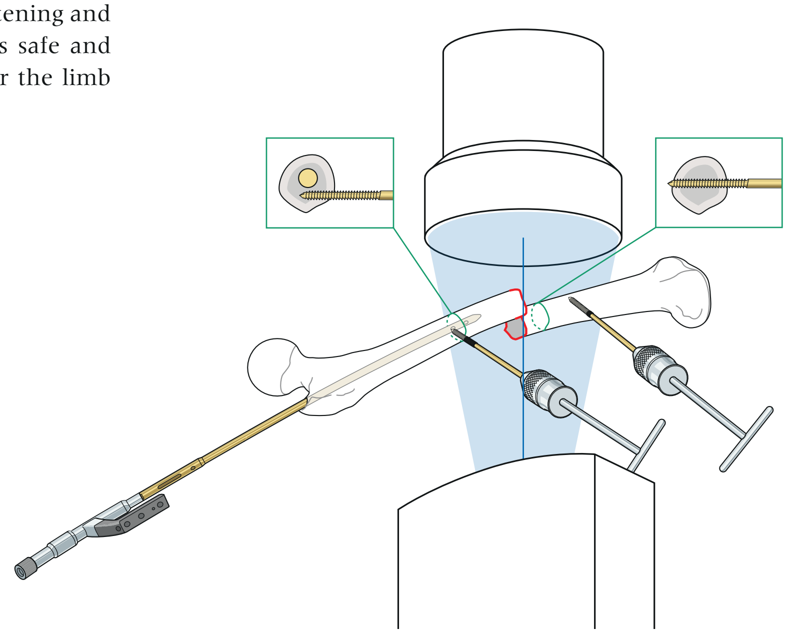
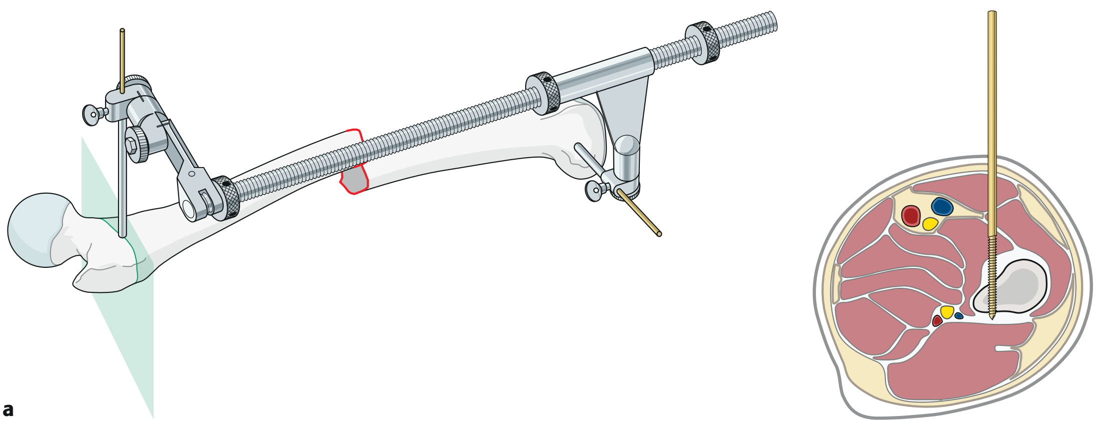


Fig 3.3.1-5 The use of Schanz screws for reduction. The Schanz screws are placed monocortically in the proximal fragment and bicortically in the distal fragment. With two universal chucks with T-handle, the fragments may be manipulated under C-arm control (AP view). The orientation in the sagittal plane is obtained by feeling the fragments touching each other.

In cases of delayed intramedullary nailing with shortening of the limb, the use of a large distractor may be essential for restitution of length and axis. Care must be taken since the single Schanz screw tends to bend and rotate under strain. If a distractor is not available, a tube-to-tube external fixator and a distraction tool can be used for the same purpose (**Fig 3.3.1-6**). Specific modular fracture reduction frames, including circular frames, are in use as well.

Intramedullary nailing of fractures in the metaphysis is associated with a higher rate of malalignment. Strong muscle pull and a wide medullary canal can lead to malposition, even with locking. Screws placed adjacent to the intramedullary nail can prevent lateral or medial translation in both the tibia and the femur. These blocking screws, also called Poller screws, decrease the width of the metaphyseal medullary canal, forcing the intramedullary nail to the center



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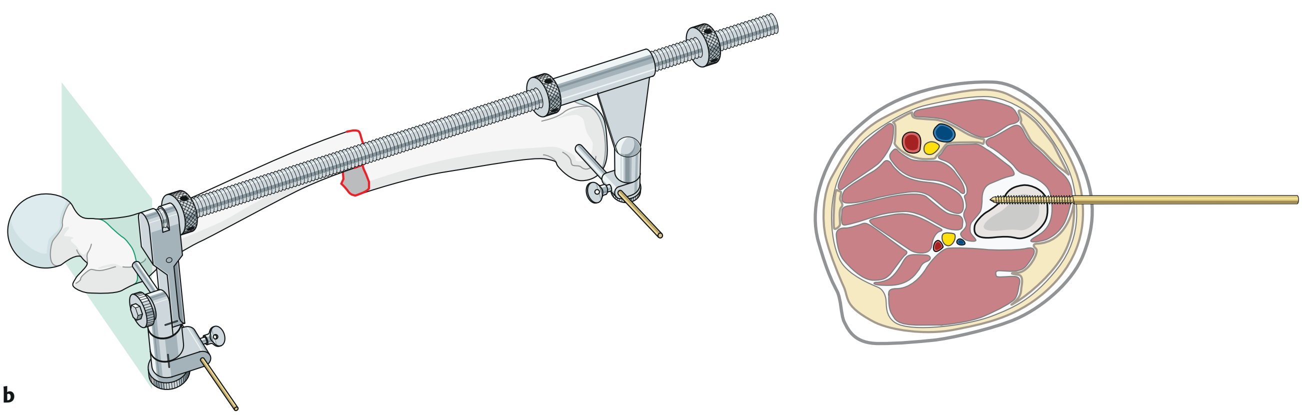


b

Fig 3.3.1-6a–b The use of a distractor for reduction.

a Standard application of the large distractor. The AP Schanz screw is inserted just proximal to the lesser trochanter, medial to the medullary canal, and lateral to the medial cortex. In the cross-section the safe distance of this Schanz screw to the neurovascular structures in the femoral triangle can be appreciated.

b Alternate application, with both Schanz screws applied laterally. The proximal Schanz screw usually interferes with the insertion handle of the intramedullary nail, so the distractor has to be removed before the nail is fully introduced.

of the medullary cavity and also increasing the mechanical stiffness of the bone-implant construct. They can also be applied to narrow the AP diameter of the medullary canal to prevent deformity in the coronal plane. Poller screws can be used for alignment, stabilization, and manipulation. The screw is placed perpendicular to the direction in which the implant might displace (**Fig 3.3.1-7**, **Video 3.3.1-6**)

In oblique metaphyseal fractures of the distal tibia or femur, the Poller screw may be helpful for stabilization, as shear forces are transformed into compression forces (**Video 3.3.1-7**).

The Poller screw may help to prevent displacement in revision surgery where there is deformity from a previously misplaced intramedullary nail. The new nail tends to slip into the old nail path but this can be prevented by a carefully placed Poller screw (**Fig 3.3.1-8**). The same technique can be used in situations where the entry point for the nail was originally poorly chosen, forcing the proximal bone fragment into malalignment: the intramedullary nail must be removed temporarily and the Poller screw placed to block the incorrect path while the intramedullary nail is reinserted.

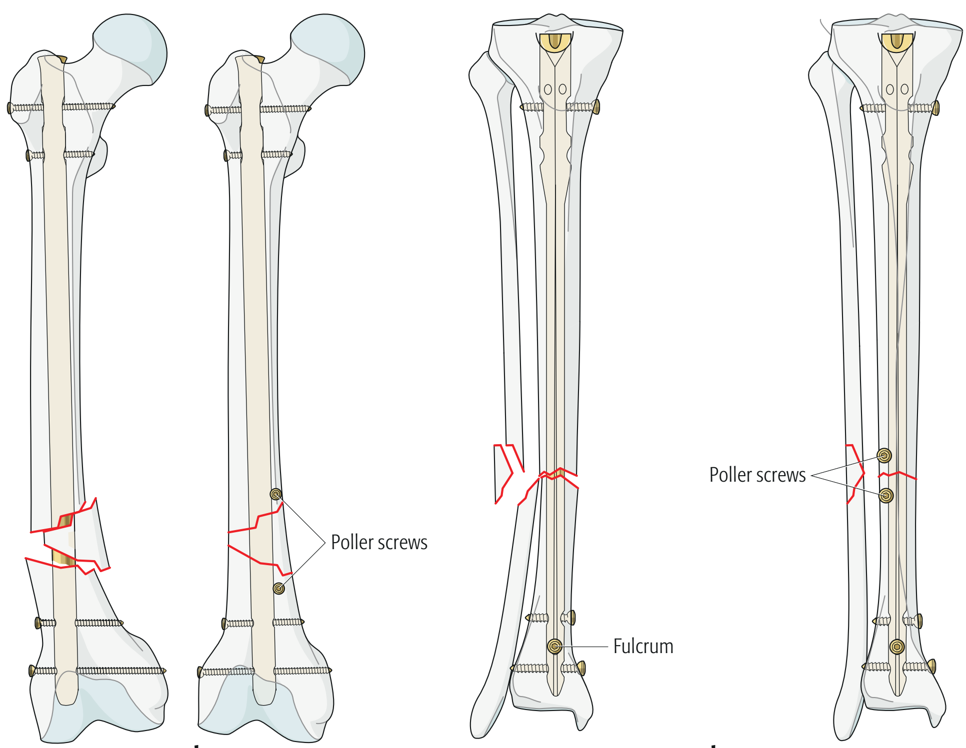


Fig 3.3.1-7a–d With the aid of Poller screws, malalignments can be prevented or corrected, while stability is simultaneously increased.

a Example of a distal femoral fracture: due to the large discrepancy between medullary canal and nail diameter, the intramedullary nail may move a few millimeters sideways along the interlocking screws, which results in varus or valgus deformity.

b Placement of one (distal) or two (distal and proximal) Poller screws before nail insertion prevents malalignment and increases stability (**Video 3.3.1-6**).

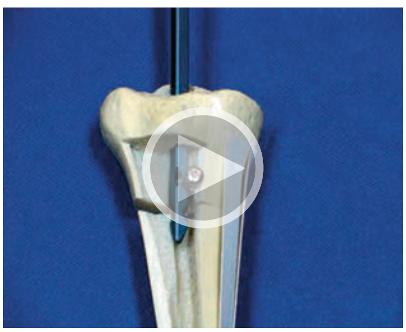
c Example of a distal tibial fracture: despite the presence of an AP screw, displacement in the coronal plane can occur in cases of short distal fragments or poor bone stock. The AP screw acts as a fulcrum in these cases.

d Closed reduction and either unilateral or bilateral support with Poller screws placed bicortically in the sagittal plane before nail insertion prevents angulation in the coronal plane.

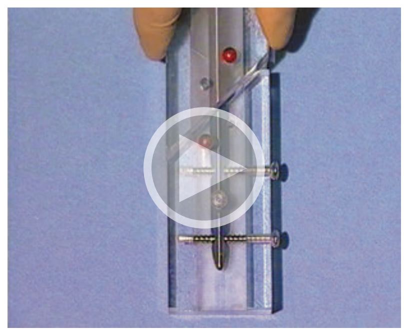
Exact closure of the fracture gap may be challenging in long oblique and spiral fractures, especially in subtrochanteric femoral fractures. Inserting the nail does not necessarily lead to an appropriate fracture reduction. In such a situation, mini open reduction or percutaneously applied cerclage wires or cables may facilitate fracture reduction. It has been shown that one or two circumferential wires are safe as long as the bone is not devitalized. Wires should be retained to prevent redisplacement after intramedullary nail fixation.

4.3.4 Sequence of locking

In simple diaphyseal fractures with good fracture apposition and no gap, the sequence of locking is not critical. However, intramedullary nails can produce fracture distraction that may cause a significant rise in compartment pressure and/or delay fracture healing. If the intramedullary nail is statically locked, the weight-bearing load is directly transmitted to the interlocking screws, which will eventually fail. Axial deformities are also more likely to develop, especially in



Video 3.3.1-6 Poller screws inserted in the correct way act as fulcrum to redirect the intramedullary nail.



Video 3.3.1-7 Poller screws can be used for alignment, stabilization, and manipulation.

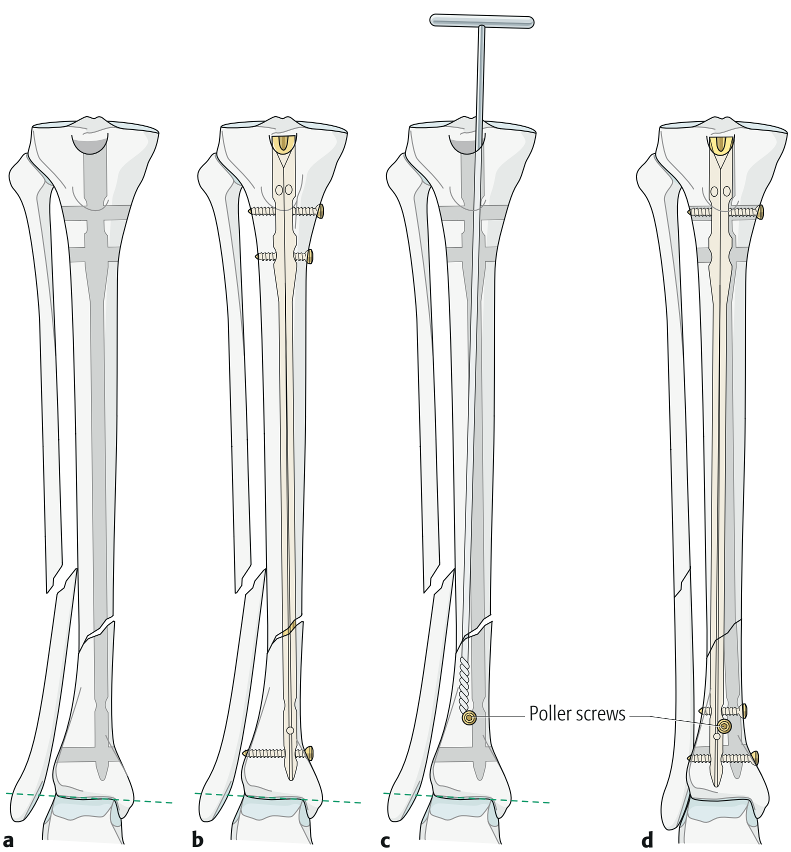


Fig 3.3.1-8a–d Poller screw as a reduction tool in a malunited fracture.

- **a** The fracture healed with valgus malalignment. After nail removal, a refracture occurred.
- **b** Since the original nail path is sclerotic, the new intramedullary nail follows the preexisting path with the same malalignment.
- **c** This problem can be solved by using a Poller screw as a reduction tool: The Poller screw is placed in the old intramedullary nail path to block it, while a new path is prepared with a hand reamer.
- **d** Once the new nail path has been prepared, the new intramedullary nail is inserted and locked, while the Poller screw remains in place.

distal metaphyseal fractures. Locking of the distal end is now recommended as a first step. This gives the opportunity to apply the backstroke technique to adapt and compress the fracture (**Fig 3.3.1-9**). If the intramedullary nail length has been correctly chosen, there should be no problem; otherwise the intramedullary nail may protrude proximally by a few millimeters.

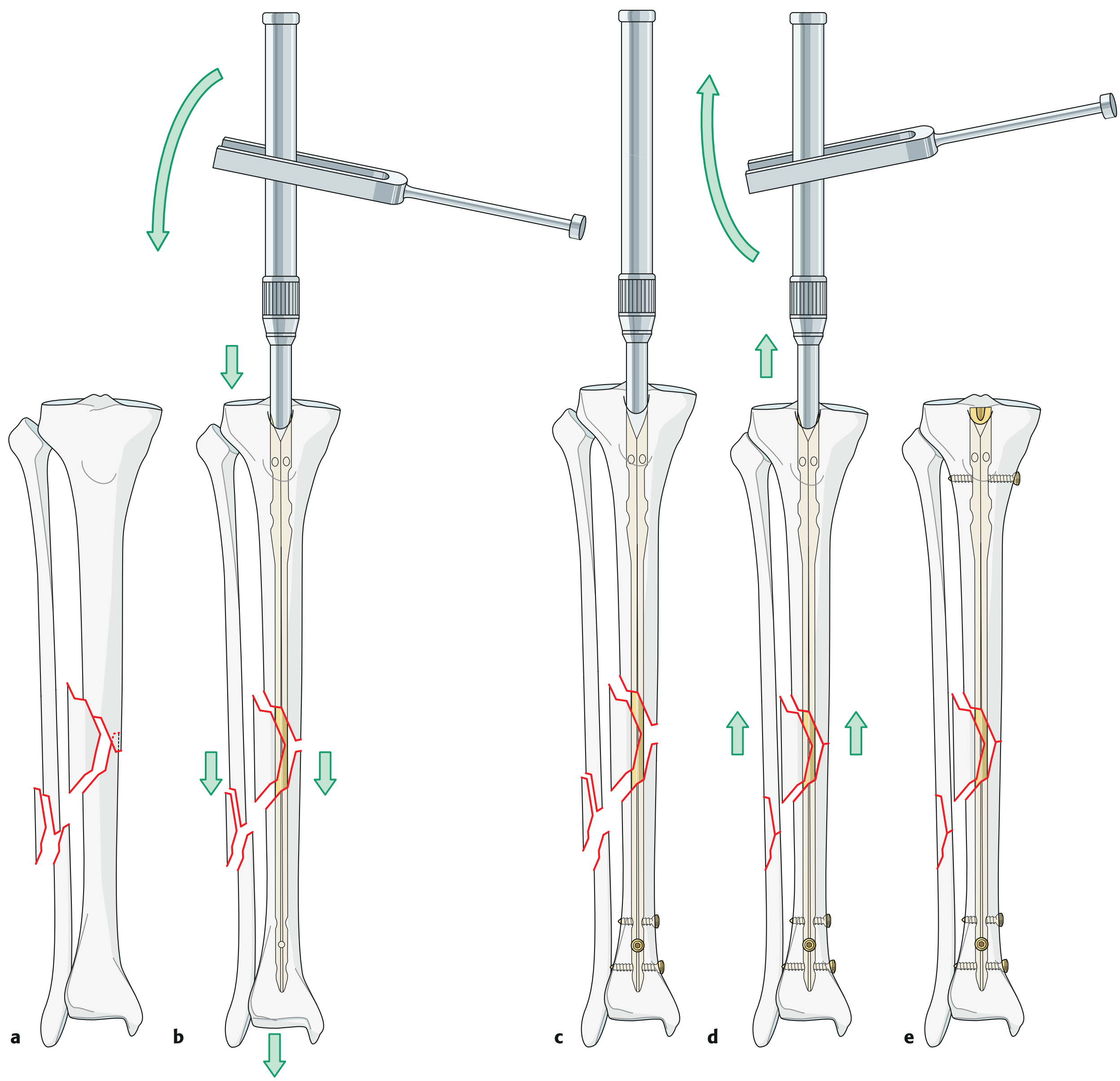


Fig 3.3.1-9a–e Backstroke technique for correction of fracture distraction.
a–b Insertion of an unreamed intramedullary nail frequently results in fracture distraction, which may worsen a compartment syndrome and delay healing.
c Distal locking first with three interlocking screws (increasing strength).
d Careful backstrokes under image intensifier control, until main fragments are reduced or the planned length is achieved.
e Proximal locking, dynamic or static, according to the fracture pattern and fracture location. If the intramedullary nail protrudes proximally, a shorter one should be chosen.

4.3.5 Intraoperative techniques for the control of alignment

Length

Inserting the distal interlocking screws first has the advantage that the distal fragment is fixed to the intramedullary nail. Any further reduction maneuvers can be performed with the insertion handle. In all type C fractures and spiral fractures (A1), reduction and especially length, should be radiologically assessed after distal locking.

To assess length in femoral fractures, the upper margin of the femoral head is brought into line with the measuring device under image intensification (**Fig 3.3.1-1**). This has the length of the contralateral femur marked on it with a clip (femoral head—lateral femoral condyle). Subsequently, the knee joint is viewed and any length discrepancy can be measured between the lateral femoral condyle and the position of the clip. By using a ram with a handle, limb length can be continuously adjusted in both directions (**Fig 3.3.1-10**). It is much easier to evaluate the length of the tibia than that of the femur, although clinical measurement usually suffices for both.

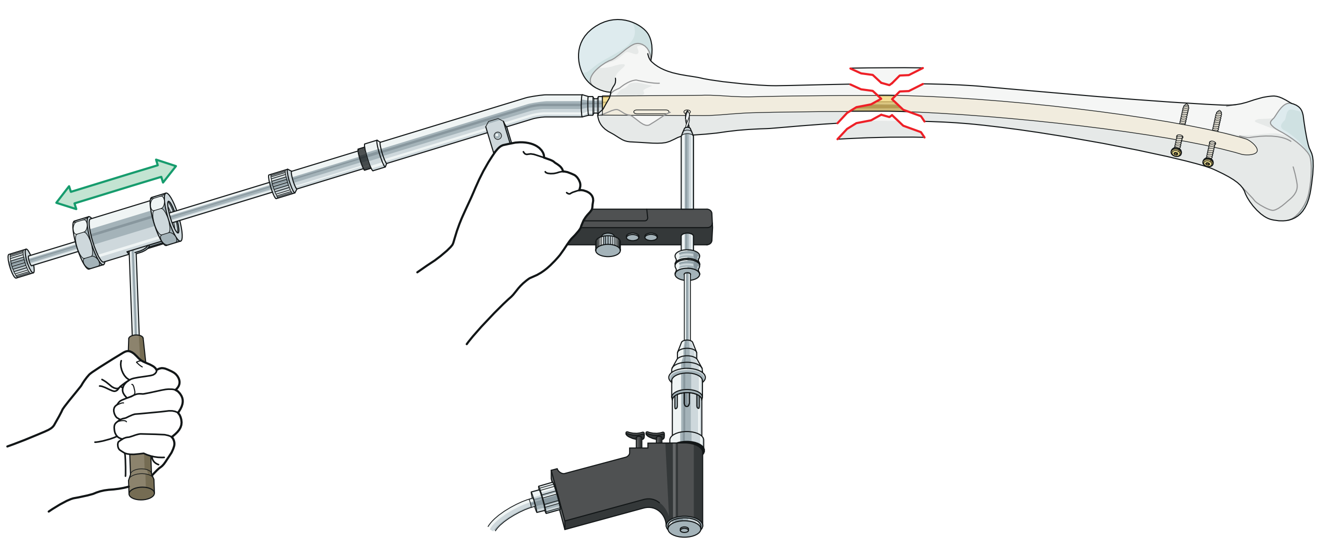


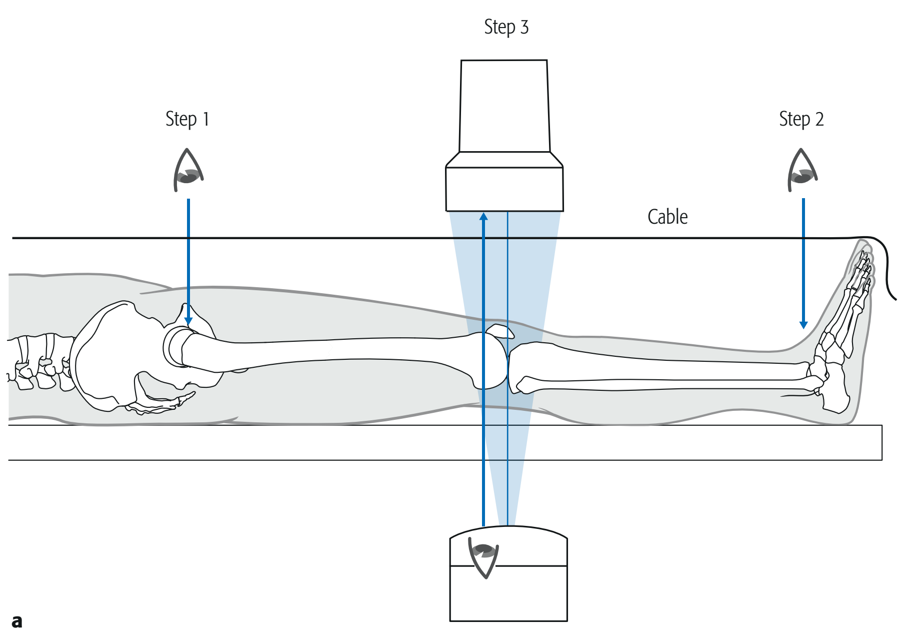
Fig 3.3.1-10 Control of length after distal locking with the sliding hammer and the insertion instruments in place.

Axial alignment

In simple tibial and femoral midshaft fractures, coronal and sagittal plane alignment is usually not a problem. Once the nail passes the fracture, the fracture will remain reduced. The femoral neck angle can be measured and checked by image intensifier. However, the evaluation of the correct weight-bearing axis is more difficult, especially in complex or metaphyseal fractures. The cable technique greatly facilitates intraoperative assessment of axis in the coronal plane with the image intensifier centered on the knee joint. Varus/valgus alignment can now be determined using the projection of the cable (**Fig 3.3.1-11**). The sagittal alignment is determined by lateral x-ray.

Rotation

There are several methods for intraoperative assessment of the rotation of femoral and tibial fractures. Clinical judgment is not precise and depends on the position of the patient and the leg during surgery. Preoperatively, the rotation of the intact limb is established with the knee and the hip flexed at 90°. Intraoperatively, after intramedullary nailing and temporary locking of the fractured bone, rotation is checked again. To do this correctly the insertion handle has to be removed. Draping both limbs facilitates intraoperative assessment of the rotation.



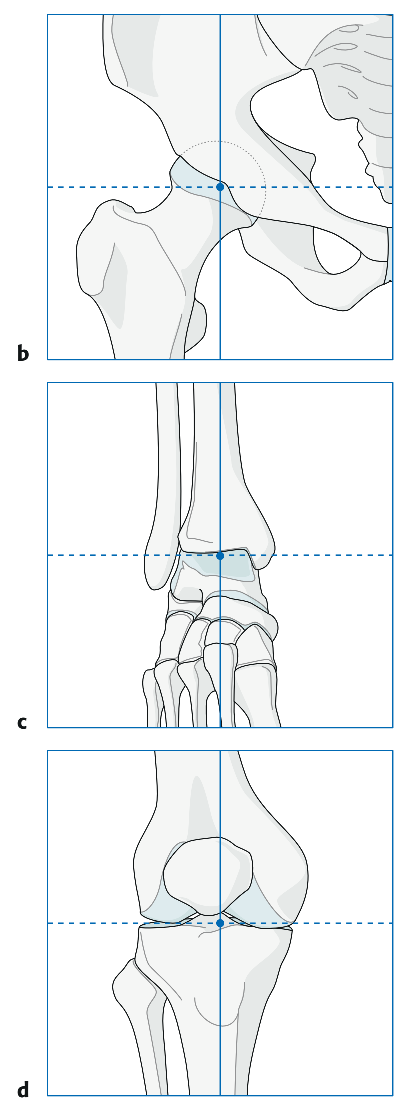


Fig 3.3.1-11 Cable technique for checking alignment in the coronal plane.

a The knee is fully extended and the patella must face anterior.

b Step 1: With the image intensifier beam vertical, the center of the femoral head is centered on the screen. A marker pen is then used to mark the center of the femoral head on the patient's skin.

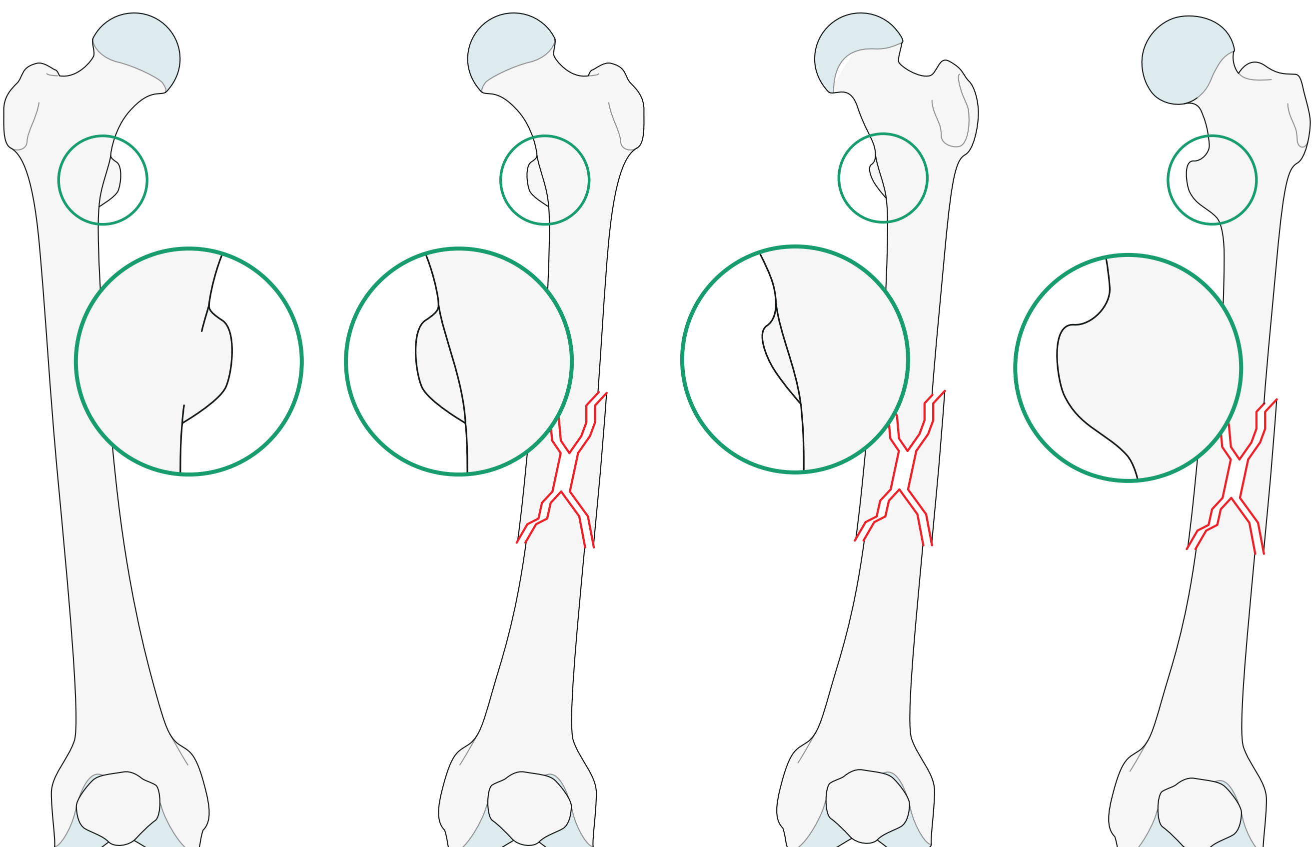
c Step 2: In a similar way the center of the ankle joint is marked. An assistant then spans the cautery cable between these two surface markings.

d Step 3: When the knee joint is viewed with image intensifier, the cable should run slightly medial to the center of the knee. Any deviation of the projected cautery cable from the center of the joint indicates the axial deviation in the frontal plane.

In the tibia, rotation should be checked with the knee in flexion and the foot dorsally flexed. However, as well as comparing the position of the feet, the range and symmetry of foot rotation also has to be taken into account.

Several radiographic signs can be helpful in assessing femoral rotation. These include:

- Shape of the lesser trochanter (**Fig 3.3.1-12**)
- Thickness of the cortices of the proximal and distal main fragments (cortical step sign)
- Difference in bone diameters



a b c d

Fig 3.3.1-12a–d Intraoperative radiological assessment of rotation. The shape of the lesser trochanter is compared with the contralateral side (lesser trochanter shape sign).

a Before positioning the patient, the shape of the lesser trochanter of the intact opposite side (patella facing anterior) is stored in the image intensifier.

b After distal locking with the patella facing anterior, the proximal fragment is rotated until the shape of the lesser trochanter matches the stored view of the intact side.

c With external malrotation, the lesser trochanter is smaller and partially hidden behind the proximal femoral shaft.

d With internal malrotation, the lesser trochanter appears enlarged.

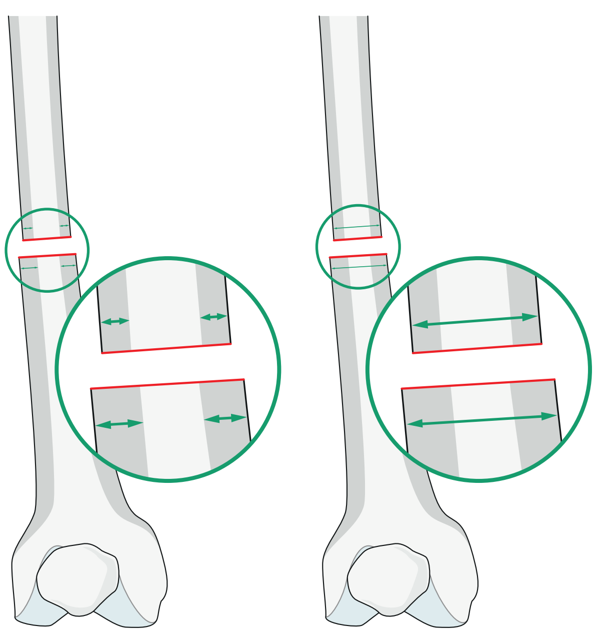
The x-ray contour of the lesser trochanter in relation to the proximal femoral shaft depends on the rotation of the bone. Preoperatively, the shape of the lesser trochanter of the uninjured limb (with the patella facing anterior) is analyzed and stored in the image intensifier.

Before proximal locking is performed, the proximal fragment can be rotated around the intramedullary nail using a Schanz screw (while the patella faces anterior), until the outline of the lesser trochanter matches the stored image of the uninjured side. With external malrotation, the lesser trochanter is smaller because it is partially hidden by the femoral shaft. With internal malrotation, the lesser trochanter appears bigger (**Fig 3.3.1-12**, **Video 3.3.1-8**).

In transverse or short oblique fractures, the correct rotation may be judged by the thickness of the cortices of the proximal and distal main fragments (cortical step sign). This is less reliable, however, than the lesser trochanter shape sign (**Fig 3.3.1-13**). In simple diaphyseal fractures, the fracture interdigitation can be used as a clue for correct rotation. If a fracture gap is present it is usually caused by distraction or malrotation.

Finally, the sign of bone diameter may be applied at levels where the bone diameter is rather oval than round. With malrotation, the transverse diameter of the proximal and distal fragment is projected differently. This sign is not that reliable (**Fig 3.3.1-13**).

Video 3.3.1-8 Anatomical landmarks and their use in judging rotational alignment (lesser trochanter shape sign).



a b

Fig 3.3.1-13a–b Radiological signs of malrotation depending on the cortical thickness and bone diameter.

- **a** Cortical step sign: in the presence of considerable rotational deformity, this can be diagnosed by the different thickness of the cortices.
- **b** Diameter difference sign: this sign is positive at levels where the bone cross-section is oval rather than round. With malrotation, the diameters of proximal and distal main fragments appear to be of different sizes.

4.3.6 Reduction techniques for delayed cases and management of nonunion

In delayed cases, and depending on the time interval, the surgeon faces the following problems:

- Axial deformation (shortening, angulation, and/or translation)
- Rotational deformity
- Tissue ingrowth and early callus formation that make reduction difficult
- Sclerosis at the fracture site with a sealed medullary canal
- Osteoporosis of the main fragments

These conditions make intramedullary nailing difficult because guide wires, reamers, and intramedullary nails are easily deflected and may penetrate the cortex in the wrong direction. Angular deformities can be corrected with the use of a distractor but an offset due to fragment translation is much more difficult to overcome.

In these situations, the use of Poller screws, as described earlier in this chapter, helps to guide instruments and implants in the desired direction. A temporary reduction plate may also be a useful option.

Hypertrophic nonunion after intramedullary nailing of femoral shaft fractures requires exchange nailing with the insertion of a reamed nail with a larger diameter. The increased stability this produces is usually sufficient to achieve union. Exchange nailing requires static locking to obtain maximum stability. Intraoperative compression can provide additional stability. As an alternative, the nail can be left in situ and augmentation plate fixation with or without bone grafting may be used [31]. Applying an additional plate on the lateral aspect of the femur increases rotational stability while alignment is maintained by the nail.

4.3.7 Prevention of malalignment

Selection of the correct entry point in the proximal fragment and a central position of the intramedullary nail in the distal fragment are the most important ways to avoid coronal and sagittal deformities. In proximal or distal metaphyseal fractures, the relatively loose contact between interlocking screws and the nail is a common source of malalignment. New implants with improved 3-D locking options (expert nails) are much better able to maintain stable fracture reduction [3]. Increased stability of the bone-implant construction can be obtained by temporarily adding external fixation devices, Poller screws, or plates (**Fig 3.3.1-8**).

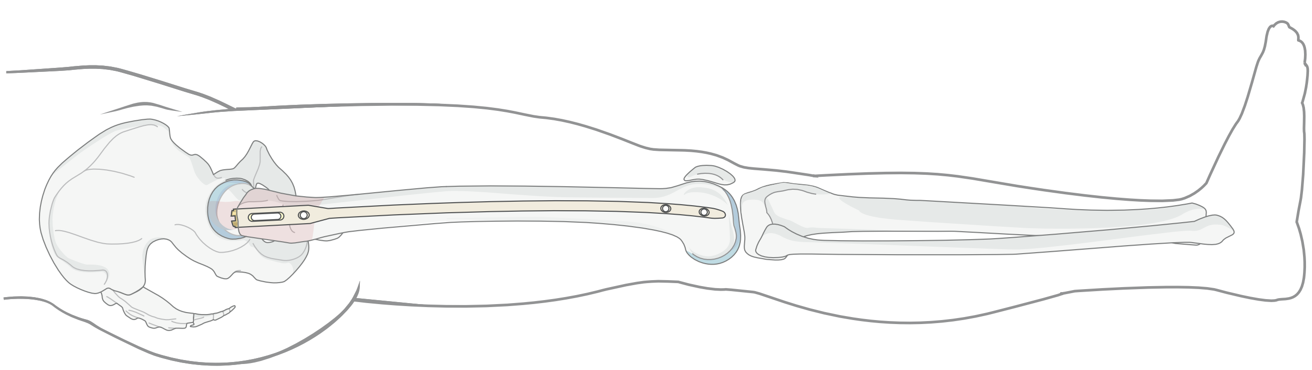
4.4 Fixation techniques/locking

4.4.1 Interlocking screws

Locking is strongly advised in reamed intramedullary nailing and is mandatory in unreamed nailing procedures since the nails are thinner. Stable fracture patterns are treated with a dynamically locked intramedullary nail, which allows axial compression but prevents rotational instability. Distal locking may be done with the freehand technique using an image intensifier (**Fig/Animation 3.3.1-14**). Proximal locking is performed through a guide attached to the insertion handle.

Distally, at least two interlocking screws are recommended because toggling may occur as there is no tight fit between the screws and the nail. This can lead to instability and malalignment, especially in the coronal plane. The insertion of two or more reduces the toggling.

> Breakage of an interlocking screw is related to the implant material, design, diameter, and surface finish, the amount of load applied, and the number of cycles.



Fig/Animation 3.3.1-14 Freehand technique of distal locking with a radiolucent drive.

Since the distal interlocking screws are usually the weakest part of the intramedullary nail construct, we recommend using the full range of locking options, especially in the distal tibia. Biomechanical data demonstrates that the fatigue strength of an intramedullary nail construct is proportional to the diameter of the interlocking screws. Increasing the number of interlocking screws as well as the interlocking screw diameter will reduce the risk of hardware failure [4].

4.4.2 Dynamization

Dynamization of an intramedullary nail allows controlled axial shortening (impaction) of a fracture with weight bearing to speed up the fracture healing rate. It is achieved by removing static locking screws (from a round hole) while a screw within an oval hole controls alignment and rotation but allows some impaction of the fracture. In the femur, dynamization of statically locked intramedullary nails is rarely advised except in transverse fracture patterns. In the tibia, it may be used in combination with a bone graft for certain fracture patterns with a high risk of delayed fracture healing. The best time seems to be 2–3 months after initial surgery.

Autodynamization results from broken locking screws and is a due to instability. Small diameter locking screws are much more prone to fail than larger diameter screws, especially when not all available locking options were used. Autodynamization may lead to compression at the fracture site and healing but in some cases screw failure increases instability and may impair solid fracture healing. If screw breakage is observed, the patient should be kept under regular review as this may be a sign of a developing non-union.

5 Contraindications

The development of new intramedullary nails designed for different indications has greatly expanded the spectrum of intramedullary nailing in terms of fracture location, fracture pattern, soft-tissue damage, and concomitant injuries.

There are, however, still several biological and mechanical concerns about intramedullary nailing, including:

- Infection at the entry site, within the medullary canal, or at pin sites (after external fixation for damage control)
- Femoral fracture(s) in polytrauma patients with lung injury, where temporary stabilization by external fixation or plating is advocated by some
- Metaphyseal fractures where fixation with interlocking screws may be insufficient to prevent malalignment
- Extremely narrow or deformed medullary canal

Classic references | Review references

6 References

1. **Utvag SE, Reikeras O.** Effects of nail rigidity on fracture healing. Strength and mineralisation in rat femoral bone. *Arch Orthop Trauma Surg*. 1998;118(1-2):7–13.
2. **Melcher GA, Claudi B, Schlegel U, et al.** Influence of type of medullary nail on the development of local infection. An experimental study of solid and slotted nails in rabbits. *J Bone Joint Surg Br*. 1994 Nov;76(6):955–959.
3. **Hansen M, Mehler D, Hessmann MH, et al.** Intramedullary stabilization of extraarticular proximal tibial fractures: a biomechanical comparison of intramedullary and extramedullary implants including a new proximal tibia nail (PTN). *J Orthop Trauma*. 2007 Nov-Dec;21(10):701–709.
4. **Kaspar K, Schell H, Seebeck P, et al.** Angle stable locking reduces interfragmentary movements and promotes healing after unreamed nailing. Study of a displaced osteotomy model in sheep tibiae. *J Bone Joint Surg Am*. 2005 Sep;87(9):2028–2037.
5. **Schemitsch EH, Kowalski MJ, Swiontkowski MF, et al.** Cortical bone blood flow in reamed and unreamed locked intramedullary nailing: a fractured tibia model in sheep. *J Orthop Trauma*. 1994 Oct;8(5):373–382.
6. **Giannoudis PV, Pountos I, Morley J, et al.** Growth factor release following femoral nailing. *Bone*. 2008 Apr;42(4):751–757.
7. **Bhandari M, Guyatt G, Tornetta P 3rd, et al.** SPRINT Trial Randomized trial of reamed and unreamed intramedullary nailing of tibial shaft fractures. *J Bone Joint Surg Am*. 2008 Dec;90(12):2567–2578.
8. **Pfeifer R, Barkatali B, Giannoudis P, et al.** *Physiological Effects Associated With Intramedullary Reaming*. Rommens PM, Hessmann MH, eds. London Heidelberg New York: Springer; 2015.
9. **White T, Petrisor BA, Bhandari M.** Prevention of fat embolism syndrome. *Injury*. 2006 Oct;37 Suppl 4:S59–67.
10. **Vallier HA, Wang X, Moore TA, et al.** Timing of orthopaedic surgery in multiple trauma patients: development of a protocol for early appropriate care. *J Orthop Trauma*. 2013 Oct;27(10):543–551.
11. **Bhandari M, Guyatt GH, Khera V, et al.** Operative management of lower extremity fractures in patients with head injuries. *Clin Orthop Relat Res*. 2003 Feb(407):187–198.
12. **Schult M, Kuchle R, Hofmann A, et al.** Pathophysiological advantages of rinsing-suction-reaming (RSR) in a pig model for intramedullary nailing. *J Orthop Res*. 2006 Jun;24(6):1186–1192.
13. **Dawson J, Kiner D, Gardner W, et al.** The reamer-irrigator-aspirator as a device for harvesting bone graft compared with iliac crest bone graft: union rates and complications. *J Orthop Trauma*. 2014 Oct;28(10):584–590.
14. **Xia L, Zhou J, Zhang Y, et al.** A meta-analysis of reamed versus unreamed intramedullary nailing for the treatment of closed tibial fractures. *Orthopedics*. 2014 Apr;37(4):e332–338.
15. **Anwar IA, Battistella FD, Neiman R, et al.** Femur fractures and lung complications: a prospective randomized study of reaming. *Clin Orthop Relat Res*. 2004 May(422):71–6.
16. **Canadian Orthopedic Trauma Society.** Nonunion following intramedullary nailing of the femur with and without reaming. Results of a multicenter randomized clinical trial. *J Bone Joint Surg Am*. 2003 Nov;85-A(11):2093–2096.
17. **Pape HC, Hildebrand F, Pertschy S, et al.** Changes in the management of femoral shaft fractures in polytrauma patients: from early total care to damage control orthopedic surgery. *J Trauma*. 2002 Sep;53(3):452-61; discussion 61–62.
18. **Canadian Orthopedic Trauma Society.** Reamed versus unreamed intramedullary nailing of the femur: comparison of the rate of ARDS in multiple injured patients. *J Orthop Trauma*. 2006 Jul;20(6):384–387.
19. **Nowotarski PJ, Turen CH, Brumback RJ, et al.** Conversion of external fixation to intramedullary nailing for fractures of the shaft of the femur in multiply injured patients. *J Bone Joint Surg Am*. 2000 Jun;82(6):781–788.
20. **Scalea TM, Boswell SA, Scott JD, et al.** External fixation as a bridge to intramedullary nailing for patients with multiple injuries and with femur fractures: damage control orthopedics. *J Trauma*. 2000 Apr;48(4):613–21; discussion 21–23.
21. **Pape HC, Giannoudis PV, Krettek C, et al.** Timing of fixation of major fractures in blunt polytrauma: role of conventional indicators in clinical decision making. *J Orthop Trauma*. 2005 Sep;19(8):551–62.
22. **Larsen LB, Madsen JE, Hoiness PR, et al.** Should insertion of intramedullary nails for tibial fractures be with or without reaming? A prospective, randomized study with 3.8 years' follow-up. *J Orthop Trauma*. 2004 Mar;18(3):144–149.
23. **Dora C, Leunig M, Beck M, et al.** Entry point soft tissue damage in antegrade femoral nailing: a cadaver study. *J Orthop Trauma*. 2001 Sep-Oct;15(7):488–493.
24. **Linke B, Ansari Moein C, Bosl O, et al.** Lateral insertion points in antegrade femoral nailing and their influence on femoral bone strains. *J Orthop Trauma*. 2008 Nov-Dec;22(10):716–22.
25. **Stannard JP, Bankston L, Futch LA,et al.** Functional outcome following intramedullary nailing of the femur: a prospective randomized comparison of piriformis fossa and greater trochanteric entry portals. *J Bone Joint Surg Am*. 2011 Aug 3;93(15):1385–91.
26. **Hessmann MH, Nijs S, Mittlmeier T, et al.** Internal fixation of fractures of the proximal humerus with the Multiloc nail. *Oper Orthop Traumatol*. 2012 Sep;24(4-5):418–431.
27. **Smekal V, Irenberger A, Struve P, et al.** Elastic stable intramedullary nailing versus nonoperative treatment of displaced midshaft clavicular fractures-a randomized, controlled, clinical trial. *J Orthop Trauma*. 2009 Feb;23(2):106–12.
28. **Farhang K, Desai R, Wilber JH, et al.** An anatomical study of the entry point in the greater trochanter for intramedullary nailing. *Bone Joint J*. 2014 Sep;96-B(9):1274–1281.
29. **Sanders RW, DiPasquale TG, Jordan CJ, et al.** Semiextended intramedullary nailing of the tibia using a suprapatellar approach: radiographic results and clinical outcomes at a minimum of 12 months follow-up. *J Orthop Trauma*. 2014 Aug;28 Suppl 8:S29–39.
30. **Giannoudis PV, Snowden S, Matthews SJ, et al.** Friction burns within the tibia during reaming. Are they affected by the use of a tourniquet? *J Bone Joint Surg Br*. 2002 May;84(4):492–496.
31. **Hakeos WM, Richards JE, Obremskey WT.** Plate fixation of femoral nonunions over an intramedullary nail with autogenous bone grafting. *J Orthop Trauma*. 2011 Feb;25(2):84–89.

7 Acknowledgments

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3.3.2 Bridge plating

Friedrich Baumgaertel

1 Introduction

Plate fixation of fractures is a form of stabilization with the potential for both load-bearing and load-sharing properties. Functional treatment of the limb to preserve muscle strength, coordination, and joint mobility depends on the stability provided by the plate-bone construction. Fracture consolidation is to be expected if the mechanics of fixation and the biology of the fracture are compatible and mutually beneficial.

Biological bridge plating uses the plate as an extramedullary splint fixed to the two main fragments and spanning the fracture zone that is left virtually untouched. Length, alignment, and rotation are restored but anatomical reduction of each fragment is not attempted.

This concept produces relative stability and preserves the natural fracture biology to achieve rapid callus formation and fracture consolidation.

Bridge plating techniques are applicable to all multifragmentary long-bone fractures and where intramedullary nailing or conventional plate fixation is not suitable (Fig 3.3.2-1).

With direct fracture reduction and plate fixation with absolute stability, the viability of soft tissues and bone fragments may be jeopardized. This risk exists to a lesser degree in simple fractures (with less soft-tissue injury and less dissection) and thus has less consequence on fracture healing. Fracture surgery must maintain vascularity at the fracture site. This calls for the use of bridging techniques in fracture patterns with significant fragmentation.

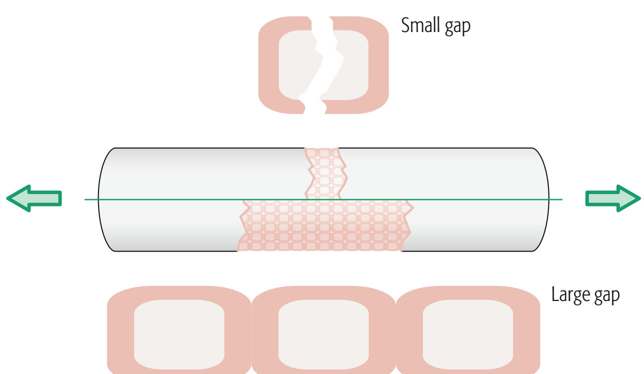
Simple type A diaphyseal fractures can be successfully treated with intramedullary nailing, a technique of relative stability, or by anatomical reduction and compression plate fixation, providing absolute stability.

Recent developments in plate design, including angular stability of the plate-screw construct with locking screws, have extended the indication for bridge plating to fractures with less fragmentation. Submuscular plates inserted using minimally invasive approaches and using locking head screws placed well away from simple fractures, can provide relative stability and subsequent bone healing with callus formation similar to intramedullary fixation.

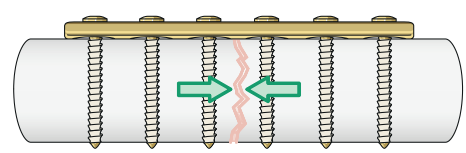
Bridging simple type A diaphyseal fractures to produce relative stability can lead to delayed or nonunion and plate failure. If the soft tissues allow the surgeon to safely achieve absolute stability, this remains the method of choice for plating simple fracture patterns.

Fig 3.3.2-1 Multifragmentary fractures of femur and tibia (33C3 and 41C2). There is also severe soft-tissue injury.

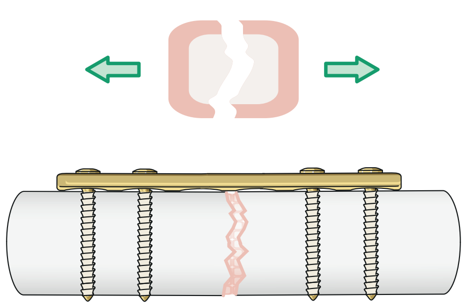
Bridge plating of simple fracture patterns should be avoided because the strain at the fracture site will be above the strain-tolerance of the tissue within the fracture site and so fracture healing will not take place (**Fig/Animations 3.3.2-2–5**). In multifragmentary type C diaphyseal fractures with multiple fragments, a bridging plate allows micromovement between the different fragments but strain is within the strain tolerance of healing tissue, allowing normal callus formation (**Fig/Animation 3.3.2-5**) [1]. If a complex, multifragmentary fracture is splinted in a cast or with a bridge plate, there will be some movement between fragments. However, the system as a whole will tolerate a significant amount of deformation, since it is distributed along the whole distance of the fracture zone. Thus, strain is low and this allows tissue differentiation to progress. Callus formation between intermediate fragments can occur rapidly, even in the presence of (controlled) movement. This is the basis of the Perren strain theory (**Fig/Animations 3.3.2-2–5**). The prerequisites for successful bone healing in this situation are optimal preservation of fragment vascularity and a favorable mechanical and cellular environment for the production of callus (**Fig 3.3.2-6**, **Video 3.2.2-7**).



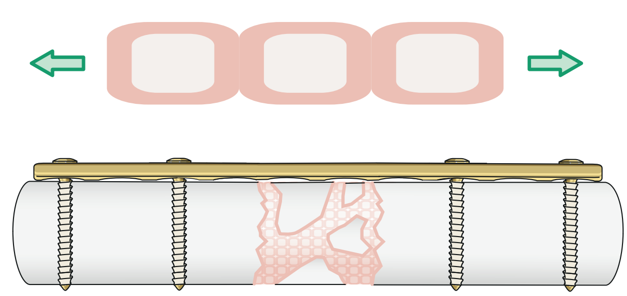
Fig/Animation 3.3.2-2 Perren's strain theory. Motion at the fracture results in deformation producing strain in the granulation tissue at the fracture site.



Fig/Animation 3.3.2-3 Perren's strain theory. A perfectly reduced simple fracture (small gap) stabilized under compression (absolute stability and low strain) heals without external callus (direct healing).



Fig/Animation 3.3.2-4 Perren's strain theory. A simple fracture (small gap) fixed with a bridging plate (relative stability) is exposed to movement (high strain). Fracture healing is delayed or will not occur at all. The plate will eventually fail.



Fig/Animation 3.3.2-5 Perren's strain theory. In a complex fracture (large gap) fixed with a bridging plate (relative stability) the strain will be low despite movement, and fracture healing will occur with callus formation (indirect bone healing).

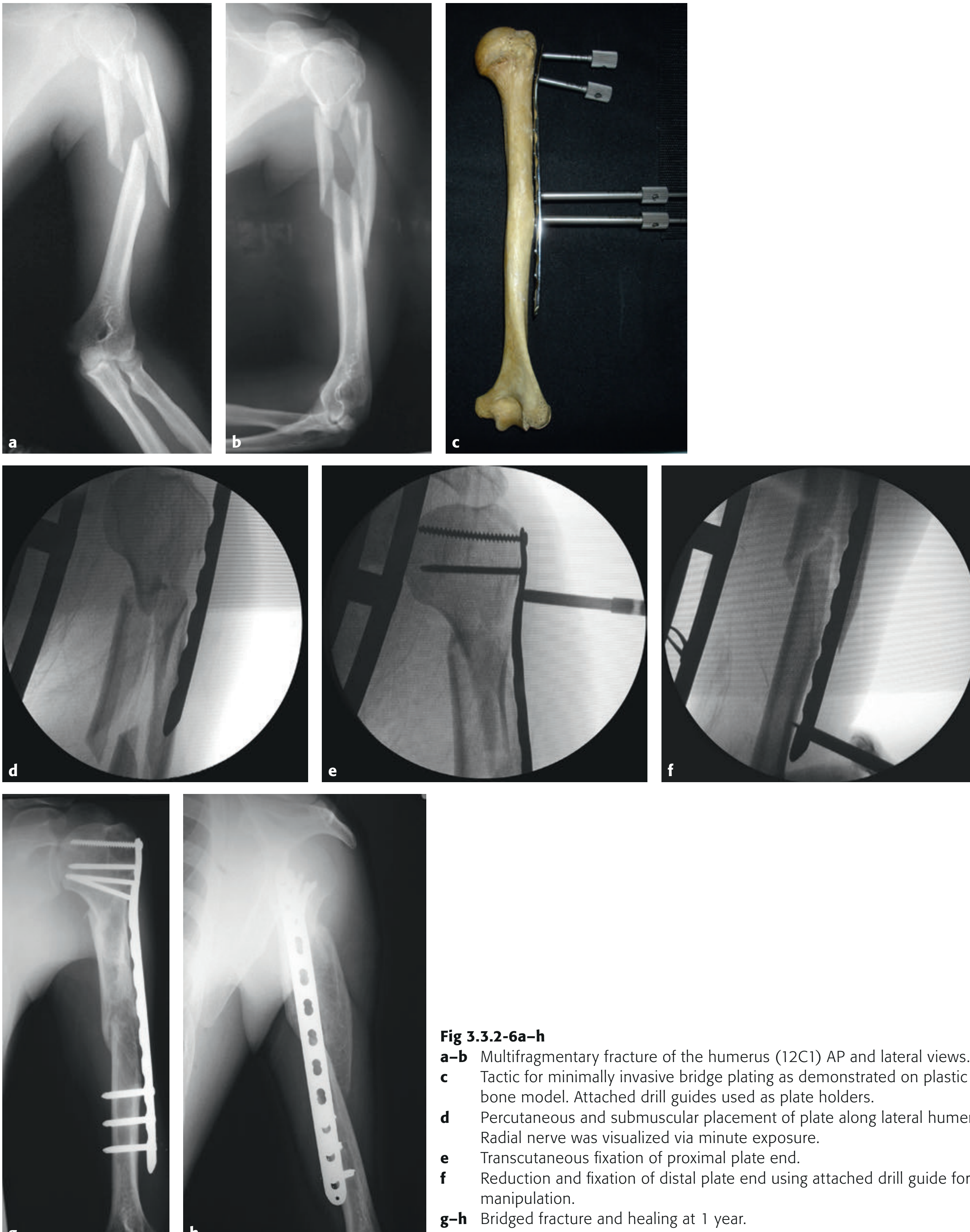


Fig 3.3.2-6a–h

a–b Multifragmentary fracture of the humerus (12C1) AP and lateral views.
c Tactic for minimally invasive bridge plating as demonstrated on plastic bone model. Attached drill guides used as plate holders.
d Percutaneous and submuscular placement of plate along lateral humerus. Radial nerve was visualized via minute exposure.
e Transcutaneous fixation of proximal plate end.
f Reduction and fixation of distal plate end using attached drill guide for manipulation.
g–h Bridged fracture and healing at 1 year.
(With permission of Theerachai Apivatthakakul).

Bone fragments, once they have been stripped of their soft-tissue attachments (periosteum, muscles, etc) will not be incorporated into the early callus because they first need to be revascularized.

In diaphyseal type C fractures, the endosteal blood supply of fragments is, as a rule, interrupted. Preservation of bone vitality relies on periosteal vascularity, which also contributes to fracture healing. In the absence of mechanical continuity between the two main fragments, maintenance of stability entirely lies with the bridging plate. The technique of wide exposure with periosteal stripping to allow precise fragment reduction and fixation by interfragmentary compression and plating should be considered obsolete and must be avoided, as it increases the risk of bone-healing complications in type C fractures [2–3]. Misapplication and misunderstanding of the principles of internal fixation are responsible for most failures and complications in this situation.

Simple metaphyseal fractures (type A) that require plate fixation are best treated with techniques of absolute stability with anatomical reduction and interfragmentary compression. In general, the same principle should be applied to simple metaphyseal fractures with simple articular fractures (C1). However, this technique is not suitable for complex metaphyseal fractures (A3) or those associated with articular fractures (C2 and C3). Anatomical reduction and absolute stability of the joint surface is paramount. The metaphyseal bone, given its better blood supply and good healing qualities, will withstand a higher degree of iatrogenic damage from surgical dissection than will the diaphysis. The critical area is not the metaphysis but its junction with the more compact bone of the diaphysis. These regions of transition remain under significant bending loads and show a tendency to delayed or failed fracture healing. In the past, liberal use of bone grafting was advocated in attempts to restore the biological activity that was compromised by the injury and the subsequent treatment.

Current plating concepts embrace the principle of achieving the correct biomechanical environment while maintaining biology. Plates incorporating angular stability have greatly facilitated bridging multifragmentary metaphyseal segments of bone.

This development allows a more flexible and individualistic approach to internal fixation, based on the personality of the injury. Operative stabilization of a complex multifragmentary fracture requires fracture reduction without interfering with the blood supply and a fixation device that maintains length, alignment and rotation to produce a biological and mechanical environment that stimulates rapid healing by callus (see chapter 3.1.3).

2 Indirect reduction techniques

Biological or bridge plating is usually applied following some form of indirect reduction (see chapter 3.1.3).

The goal of indirect reduction is to manipulate fragments into the correct position without opening the fracture site, thus minimizing further damage to the bone blood supply [4–6]. The mechanical principle underlying indirect reduction is distraction. This principle applies to diaphyseal as well as to metaphyseal bone. The muscular envelope surrounding the diaphysis of long bones provides the mechanical environment for indirect reduction, since a controlled pull on the muscle and periosteal attachments of any single fragment often produces correct alignment. A muscle envelope under distraction exerts concentric (hydraulic) pressure on the shaft, easing fragments into place. This also holds true for metaphyseal and periarticular bone, although the distraction required to align fragments is transferred through capsular tissues, ligaments, tendons, and muscular attachments. This phenomenon, regularly used as part of nonoperative fracture management, is described by the term "ligamentotaxis", coined by Vidal [7]. Traction applied by a traction table to an entire limb produces indirect reduction of a fracture. However, the use of an implant or large distractor attached to a single bone controls reduction more effectively and permits subtle adjustments as well (**Video 3.3.2-1**). Indirect reduction techniques can use a distractor, external fixator, or plate as reduction tools, sometimes in combination. Other tools for indirect reduction include plates

Video 3.3.2-1 The femoral distractor is an excellent tool for indirect fracture reduction.

in conjunction with the articulated tension device, bone spreaders, or screws (**Fig/Animation 3.3.2-7**).

3 Implant considerations

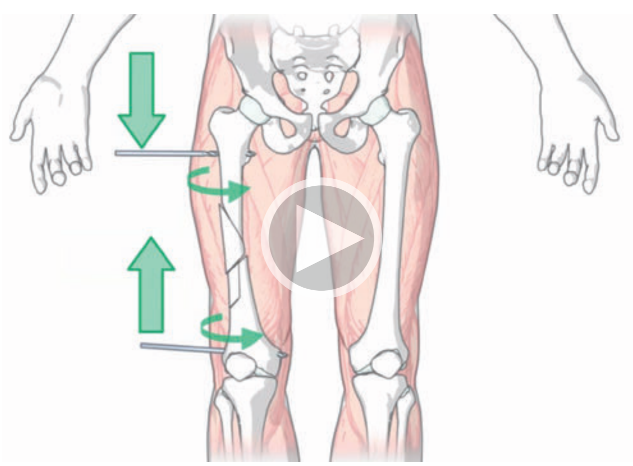
In biological or bridge plating, the surgeon must study the fracture morphology, carefully plan the reduction, and finally choose a plate appropriate to the anatomical location and the configuration of the fracture.

New plates designed for different anatomical locations have different thicknesses, shapes, and widths within the implant itself. Combination holes receiving either locking screw heads or conventional screw heads and/or individual holes that take only locking head screws provide plate functions as required by the fracture pattern. Angular stability at the metaphyseal end of a locking plate allow it to function as a fixed angle device while locking head screws at both ends of the plate allow it to function as an internal fixator. Both techniques allow the implant to act as a bridge plate

Most plates can function as a bridging plate, whether they are conventional (LC-DCP) or locking (LCP).

The common denominator in all bridge plating is the use of a long plate as a splint on the outside of a bone, in the same way a nail splints the bone from within or an external fixator spans the fracture and holds the bone from the outside. Splinting of complex fractures has been a principle applied by surgeons for many years, but it has only recently been accepted as a principle of plate fixation (**Fig 3.3.2-8**).

The original bridge plate was a dynamic compression plate (DCP) used as a "wave" plate, with a central curved segment leaving room for a bone graft. The wave plate reduces interference with the vascular supply of the fracture site by avoiding bone contact but bending forces to the plate, which functions as weight-bearing implant, are considerable. Bridging fractures with a conventional DCP used in minimally invasive plate osteosythesis (MIPO) lacks the mechanical advantage of angular stability achieved by a plate using locked screws (LCP).



Fig/Animation 3.3.2-7 Shortening and angulation of femoral fracture and indirect reduction by distraction between Schanz screws.

Fig 3.3.2-8a–k A 54-year-old woman was hit by a motor vehicle while walking.
a–b Distal femoral multifragmentary fracture involving the medial and lateral femoral condyles in coronal plane (bilateral Hoffa fractures).

Fig 3.3.2-8a–k (cont) A 54-year-old woman was hit by a motor vehicle while walking.

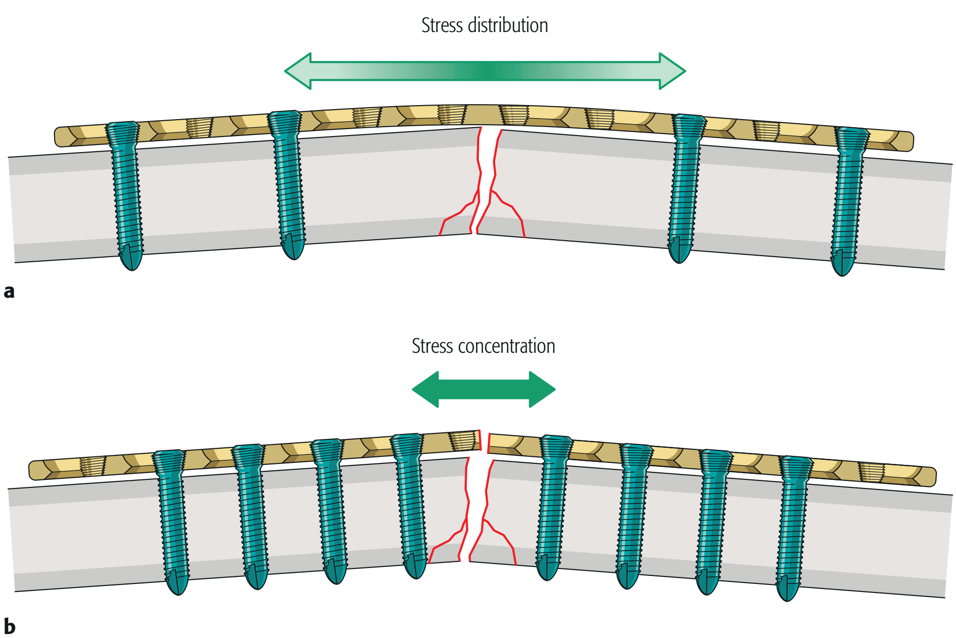
c–e The articular fragments were fixed with countersunk 3.5 mm lag screws.

f–g Immediately postoperative x-rays demonstrated the correct mechanical axis, although the upper part of the plate was not well adapted to the bone due to variation of bone anatomy.

h–k Six months postoperatively the patient had good range of motion and x-rays showed bone consolidation.

Long plates with a long working length allow the distribution of bending stresses over a long segment of the plate and the stress per unit area is correspondingly low. This avoids high strain at the fracture site and reduces the risk of plate failure (Fig/Animation 3.3.2-9).

In simple (type A) fractures, repetitive bending stresses will be concentrated and centered on a short segment of a plate with a high risk of failure. If stress is concentrated on a screw hole, it may break more easily due to fatigue. The incidence of mechanical failure can be considerably reduced if longer plates are used despite short zones of comminution, so that stresses are deliberately distributed over a proportionately longer section of the plate. This is accomplished by fixing the end of the plate over longer segments, well away from the fracture, and spacing the screws. This produces an elastic construction [8, 9]. Fewer screws are needed, especially when using locked screws, since screw pull-out force increases with the distance to the fracture zone (see chapter 3.3.4) (**Fig 3.3.2-10**). This internal fixator principle is based on the locking head screws providing angular stability and minimizing the area of contact between plate and bone, thus interfering less with periosteal blood supply while enhancing axial stability. The LCP also displays a more even distribution of strength throughout the plate, reducing stress risers at a screw hole [10].



Fig/Animation 3.3.2-9a–b If there is a fracture gap, stress concentration on one screw hole may lead to fatigue failure.

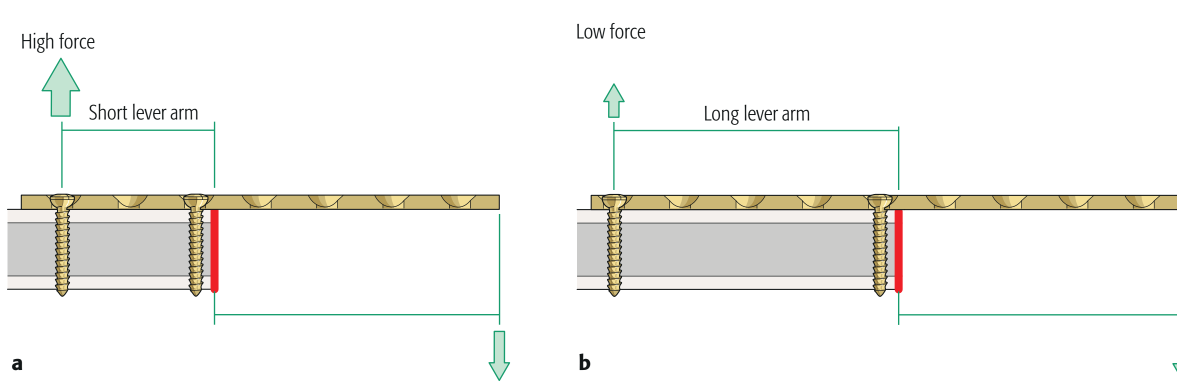


Fig 3.3.2-10 Long lever arms decrease screw loading.
a A short lever arm leads to a high pull-out force on the screw.
b Increasing the lever arm reduces the pull-out force.

4 Soft-tissue considerations

Biological plating provides relative stability, preserves vascularity around the fracture and allows controlled micromotion, resulting in more rapid and abundant callus formation, similar to that observed in intramedullary nailing or in nonoperative fracture treatment. However, the success of this operative approach greatly depends on how the surgeon handles the soft tissues and on how well the anatomical characteristics of any given fracture have been taken into consideration during the planning and execution of surgery. Newer, anatomical approaches reflect the trend to minimal exposure of the bone (see chapter 3.1.3).

The muscle envelope over the fracture site is rarely elevated from the intermuscular septum. The periosteum is left untouched and ligation of the perforating vessels should be avoided, if possible. The plate is gently inserted through a tunnel between muscle and bone, and over the periosteum.

It is most important not to damage the soft-tissue envelope around the fracture site.

The exposure can safely be extended to control the plate position, center the plate on the bone, and adjust fracture alignment at either end of the long-bridging plates. Excessive traction on the wound, to avoid a longer incision, is a poor surgical technique [11].

In the tibia, a plate can be introduced subcutaneously on the medial side. However, care should be taken not to place excessive tension on the delicate overlying skin: locking screws can result in the plate standing off the bone causing skin tension and wound healing problems [12]. For placement lateral to the tibial crest, more dissection with a sharp elevator is necessary at the proximal metaphysis. Screws are easily introduced through stab incisions but surgeons must be aware of the anatomy and potential to damage cutaneous nerves.

Other areas of application for minimal access plating include the humerus, distal femur, proximal and distal tibia [11]. These locations have distinct anatomical characteristics requiring exact plate positioning. Anatomically designed plates, in combination with locking head screws, have improved the ability to apply these techniques. The surgeon may find it necessary to combine direct open reduction of the articular components with indirect reduction and submuscular positioning of the plate for associated metaphyseal or diaphyseal fractures (**Fig 3.3.2-11**). If difficulties occur, a conventional approach is advisable and this still allows careful handling of the soft-tissues and minimal exposure of the bone itself. Even when using biological techniques, the surgeon must always be mindful of soft-tissue damage caused by the initial trauma. Soft-tissue retractors and reduction tools, such as plate holding forceps, should not be used since they leave large tracks and can cause significant soft-tissue stripping and crushing. We recommend pointed reduction forceps, ball spikes, picks, and joysticks as instruments for bone manipulation in combination with instruments of distraction.

Fig 3.3.2-11a–g Bridge plating with the less invasive stabilization system proximal lateral tibia (LISS-PLT) using minimally invasive plate osteosynthesis (MIPO).

a–b Multifragmentary articular proximal tibial fracture (41C3) extending into the tibia shaft.

c Intraoperative photograph showing the limited exposure for the articular reconstruction and the submuscular plate insertion as well as the small incisions for the more distal locking head screws. Surgeons must be aware of the position of the superficial peroneal nerve.

d–e Open reconstruction of articular components with independent lag screws. Bridging of the meta-/diaphyseal fracture zone with a 14-hole tibia LISS fixed with locking head screws to the distal main fragment. The large intermediate butterfly fragment has been reduced by two additional lag screws in AP direction.

f–g The patient was immediately allowed to freely move the limb and start partial weight bearing of 15–30 kg after 3 weeks. Follow-up x-rays after 1 year.
(With permission by Christoph Sommer.)

In grade III open fractures or closed injuries with considerable soft-tissue contusion, bridge plating is not the first choice for fixing a multifragmentary fracture in an emergency situation. Here, a bridging external fixator or the use of intramedullary nailing may be indicated (see chapters 3.3.3 and 3.3.1). Bridge plating techniques are often applied later, when the soft-tissue injury has stabilized (**Fig 3.3.2-12**).

The Masquelet technique, described in 1986 for the treatment of bone defects, uses a plate to bridge a bone defect (caused by injury or debridement), which is filled by an antibiotic cement spacer. The foreign body reaction results in a vascularized (induced) membrane, which serves as a pouch for cancellous autogenous bone grafting 6 to 8 weeks later [13].

The management of difficult fractures is demanding and requires experience, as well as careful planning of options and tactical steps. Major pitfalls are the correct axial and rotational alignment, as these can only be judged indirectly.

5 Summary

Techniques of indirect reduction in combination with bridge plating have proven, experimentally and clinically, to optimize healing in complex, multifragmentary fractures. Direct anatomical reduction and interfragmentary compression to provide absolute stability should be reserved for simple fractures with minimal soft-tissue injuries. With locking plates, the trend to minimally invasive surgery continues, so that submuscular tunneling and plate introduction will be facilitated by new reduction tools, and instruments for radiographic, endoscopic viewing and navigated surgery.

A prerequisite for successful biological plating is a sound knowledge supported by practical experience in the art and skill of conventional compression plating.

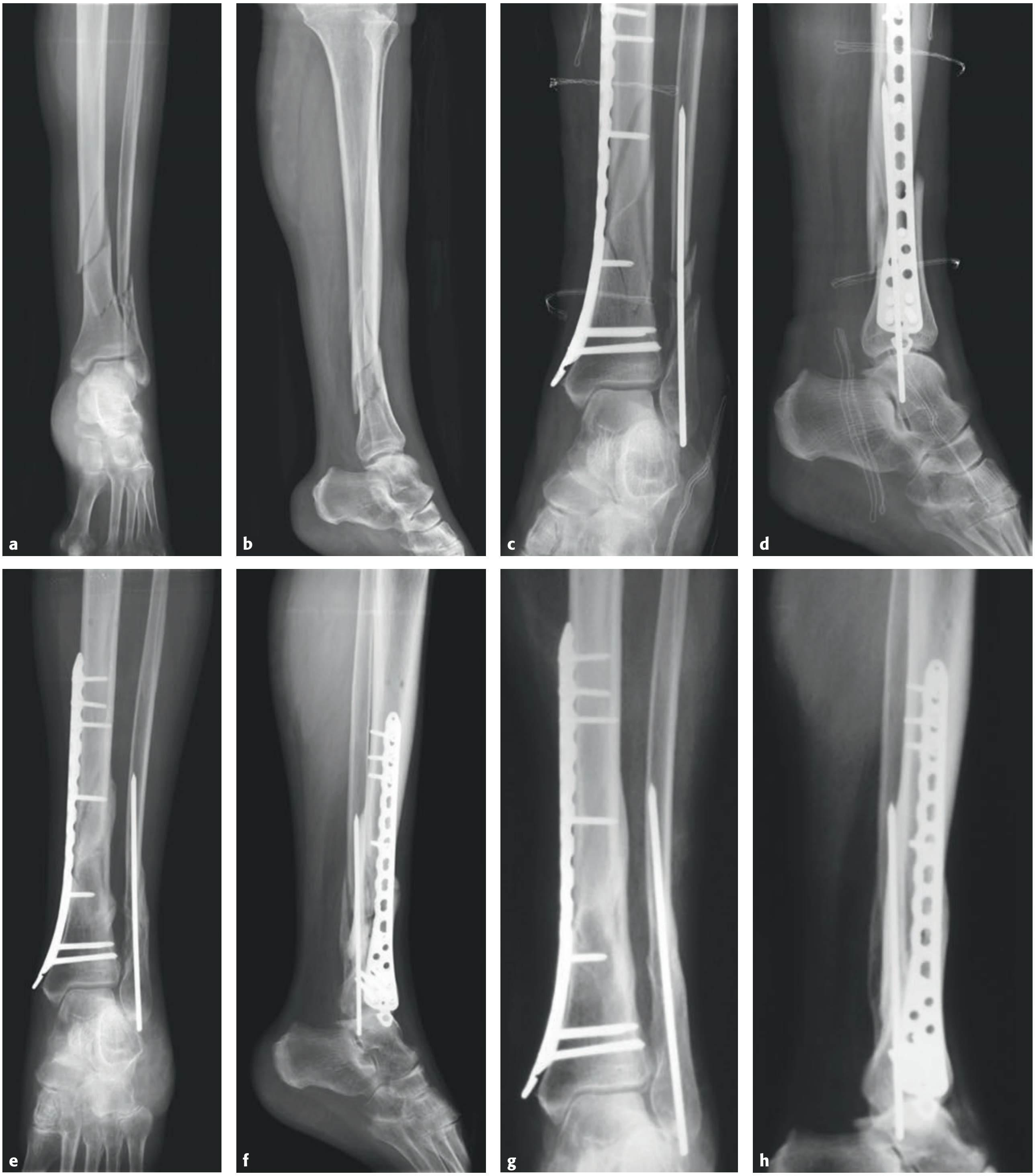


Fig 3.3.2-12a–h Closed fracture of the left lower leg (42B2).

a–b AP and lateral preoperative x-rays. Length and alignment of the bone was satisfactory. There was minor malrotation.

c–d AP and lateral postoperative x-rays. Using the distractor for indirect reduction, percutaneous bridge plating of the tibia and intramedullary splinting of the fibula were carried out. No attempt was made to achieve anatomical reduction. Intermediate screws were placed in the main fragments only. Great care was taken with skin closure at the medial malleolus to avoid tension from the underlying plate.

e–f AP and lateral views at 5 months. The fracture healed by indirect bone healing. Length and alignment were correct.

g–h AP and lateral views at 1 year. Remodeling was complete.

Classic references | Review references

6 References

1. **Perren SM.** The concept of biological plating using the limited contact-dynamic compression plate (LC-DCP). Scientific background, design and application. *Injury*. 1991;22(Suppl 1):1–41.
2. **Lies A, Scheuer I.** Die mediale Abstützung—Bedeutung und Möglichkeiten der Wiederherstellung bei Osteosynthesen. *Hefte Unfallheilkunde.* 1981;153:243–248. German.
3. **Bolhofner BR, Carmen B, Clifford P.** The results of open reduction and internal fixation of distal femur fractures using a biologic (indirect) reduction technique. *J Orthop Trauma.* 1996; 10(6):372–377.
4. **Baumgaertel F, Gotzen L.** [The “biological” plate osteosynthesis in multi-fragment fractures of the para-articular femur. A prospective study]. *Unfallchirurg*. 1994;97(2):78–84. German.
5. **Baumgaertel F, Perren SM, Rahn B.** [Animal experiment studies of “biological” plate osteosynthesis of multi-fragment fractures of the femur]. *Unfallchirurg.* 1994 Jan;97(1):19–27. German.
6. **Mast, J, Jakob R, Ganz R.** *Planning and Reduction Technique in Fracture Surgery*. Berlin Heidelberg New York: Springer; 1989.
7. **Tepic S, Remiger AR, Morikawa K, et al.** Strength recovery in fractured sheep tibia treated with a plate or an internal fixator: an experimental study with a two-year follow-up. *J Orthop Trauma*.1997 Jan; 11(1):14–23.
8. **Vidal J.** External fixation: current state of the art. In: Brooker HS, Edward CC, eds. *Treatment of Articular Fractures by “Ligamentotaxis” With External Fixation*. Baltimore: Williams & Walkins; 1979.
9. **Schmidtmann U, Knopp W, Wolff C, et al.** [Results of elastic plate osteosynthesis of simple femoral shaft fractures in polytraumatized patients. An alternative procedure]. *Unfallchirurg*. 1997 Dec; 100(12):949–956. German.
10. **Hunt SB, Buckley RE.** Locking plates: a current concepts review of technique and indications for use. *Acta Chir Orthop Traumatol Cech.* 2013; 80(34):185–191.
11. **Krettek C, Schandelmaier P, Miclau T, et al.** Transarticular joint reconstruction and indirect plate osteosynthesis for complex distal supracondylar femoral fractures. *Injury.* 1997; 28 Suppl 1:A31–A41.
12. **Krettek C, Schandelmaier P, Miclau T, et al.** Minimally invasive percutaneous plate osteosynthesis (MIPPO) using the DCS in proximal and distal femoral fractures. *Injury.* 1997; 28(Suppl 1):A20–A30.
13. **Helfet DL, Shonnard PY, Levine D, et al.** Minimally invasive plate osteosynthesis of distal fractures of the tibia. *Injury.* 1997; 28 Suppl 1:A42–A47; discussion A47–48.
14. **Giannoudis P, Faour O, Goff T, et al.** Masquelet technique for the treatment of bone defects: tips-tricks and future directions. *Injury.* 2011 Jun; 42(6):591–598.

7 Acknowledgment

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3.3.3 External fixator

Dankward Höntzsch

1 Introduction

The external fixator is one of the mainstays of operative fracture treatment. It allows "local damage control" for fractures with severe soft-tissue injuries and can be used for definitive treatment of many fractures. It provides relative stability that results in healing by callus formation. External fixation is an essential part of damage-control surgery in polytrauma, as it permits rapid stabilization of fractures with minimal additional (surgical) injury. A main indication is bone fixation in cases of bone infection. Deformity correction and bone transport are also possible with external fixation.

2 Why utilize the external fixator?

2.1 Advantages

There are various methods of internal fixation for the treatment of fractures but at certain times it is inappropriate to perform internal fixation as primary treatment. External fixation has the following advantages:

- Less damage to the blood supply of the bone
- Minimal interference with soft-tissue cover
- Rapid application in an emergency situation
- Stabilization of open and contaminated fractures
- Adjustment of fracture reduction and stability without surgery
- Minimal foreign body in the presence of infection
- Less experience and surgical skill required than for standard open reduction and internal fixation (ORIF)
- Bone transport and deformity correction possible

2.2 Indications for external fixation

2.2.1 Open fractures

External fixation is one option for the temporary or definitive skeletal stabilization of open fractures, in particular those with severe soft-tissue injury [1].

It is also useful in cases where there is a higher risk of infection, eg, delayed treatment and/or wound contamination. It has long been a useful device for managing such injuries and remains the gold standard for several reasons.

External fixation can be applied with minimal trauma, avoiding additional damage to soft tissues and bone vascularity.

2.2.2 Closed fractures

In closed fractures, external fixation is indicated for temporary bridging in severe polytrauma [2, 3] and severe closed soft-tissue contusions or degloving.

Delayed open reduction is recommended for some closed fractures with severe soft-tissue injury and polytrauma. In these cases, a temporary external fixator may be applied outside the zone of injury and, ideally, outside the zone of potential surgery to maintain the alignment of the limb while treating the soft tissues.

2.2.3 Polytrauma

External fixation should be considered for damage-control surgery in polytrauma. It can be performed rapidly and, because it is a minimally invasive technique, it will minimize any additional surgical insult to the patient [2, 3].

External fixation can be used for almost every long bone and large joint fracture. The main advantage of this approach is the rapid achievement of relative stability that helps to control pain, decrease bleeding, lessen systemic inflammatory response syndrome [3], and facilitate nursing care.

2.2.4 Articular fractures

Perfect joint reconstruction with interfragmentary compression and absolute stability, allowing early pain-free motion, is the treatment goal for articular fractures. This goal can be achieved by ORIF or, for simple fracture patterns, by a combination of interfragmentary lag screw fixation with an external fixator. This is generally a temporary measure designed to protect delicate soft-tissues associated with an unstable or complex articular fracture, or to cope with joint dislocations that do not permit primary definitive internal fixation or ligament repair. Any major joint can be bridged in this way [4, 5] but it is most common in the wrist, knee and ankle.

2.2.5 Bone or soft-tissue loss

External fixators provide the surgeon with the unique opportunity to manage major soft tissue and bone loss by primary shortening of the limb followed by secondary distraction osteogenesis to restore limb length. In some cases this will avoid the need for major plastic surgical reconstruction.

2.2.6 External fixator as a tool for indirect reduction

The external fixator can be used as a tool to perform indirect reduction during minimally invasive osteosynthesis [6]. Once the fracture has been reduced, the position is maintained by locking the external fixator while the internal fixation plate or intramedullary nail is inserted and secured. In some situations, when the internal fixation does not provide adequate stability, the external fixator can be left in situ for a short period to provide additional support.

One way to achieve minimally invasive intraoperative reduction is to apply the modular external fixator as an external reduction device.

External fixators or femoral distractors have proven their value for intramedullary nailing of the tibia. Steinmann pins are inserted in the proximal tibial, posterior to the entry point for the intramedullary nail, and in the calcaneus, and joined by long tubes. This achieves well-balanced local traction with which length, alignment, and rotation can be adjusted; the intramedullary nailing can be performed without obstruction, with the knee joint in flexion or extension (**Video 3.3.3-1**).

3 External fixation principles

3.1 Biomechanical aspects

The surgeon must understand the biomechanical principles to correctly apply an external fixation device to achieve adequate stability. At least two pins must be inserted into each main fragment through an anatomical safe zone. Pins should be spread as wide apart as possible. If the soft-tissue situation allows, pins are inserted as close to the fracture focus as possible but should not enter the fracture hematoma or degloved areas. If delayed internal fixation is planned, the pins should avoid potential incisions and surgical approaches (the zone of surgery). The connecting tube should be placed as close as possible to the bone to increase stability.

Video 3.3.3-1 Application of a distraction frame with tibial nailing.

The stiffness of the frame depends upon the following factors (**Fig 3.3.3-1**):

- Distance of the pins/Schanz screws from the fracture focus: closer means stiffer
- Distance between the pins/Schanz screws inserted in each main fragment: further apart means stiffer
- Distance of the longitudinal connecting tube/bar from the bone: closer means stiffer
- Number of bars/tubes: two are stiffer than one
- Configuration (low to high stiffness): uniplanar/A-frame/biplanar
- Combination of limited internal fixation (lag screw) with external fixation: only rarely indicated as mixing elastic with stable fixation is for temporary use only
- Thickness of Schanz screws or Steinmann pins—6 mm vs 5 mm pins (double bending stiffness)

Unstable external fixation will delay fracture healing. However, too much stiffness or rigidity of the external fixator construction may also delay fracture healing.

It may be necessary to dynamize a stable fixator configuration and increase load through the fracture site by partial or full weight bearing and/or by modifying the frame construction [7].

3.2 Pin insertion technique

When inserting a Steinmann pin or Schanz screw the following is important:

- Know the anatomy and avoid nerves, vessels, and tendons
- Do not place pins or screws into a joint
- Avoid the fracture focus and hematoma
- Avoid degloved and contused skin
- Predrill the cortex to avoid burning the bone (ring sequestrum is produced)
- Insert a Schanz screw of the correct length to allow appropriate frame construction

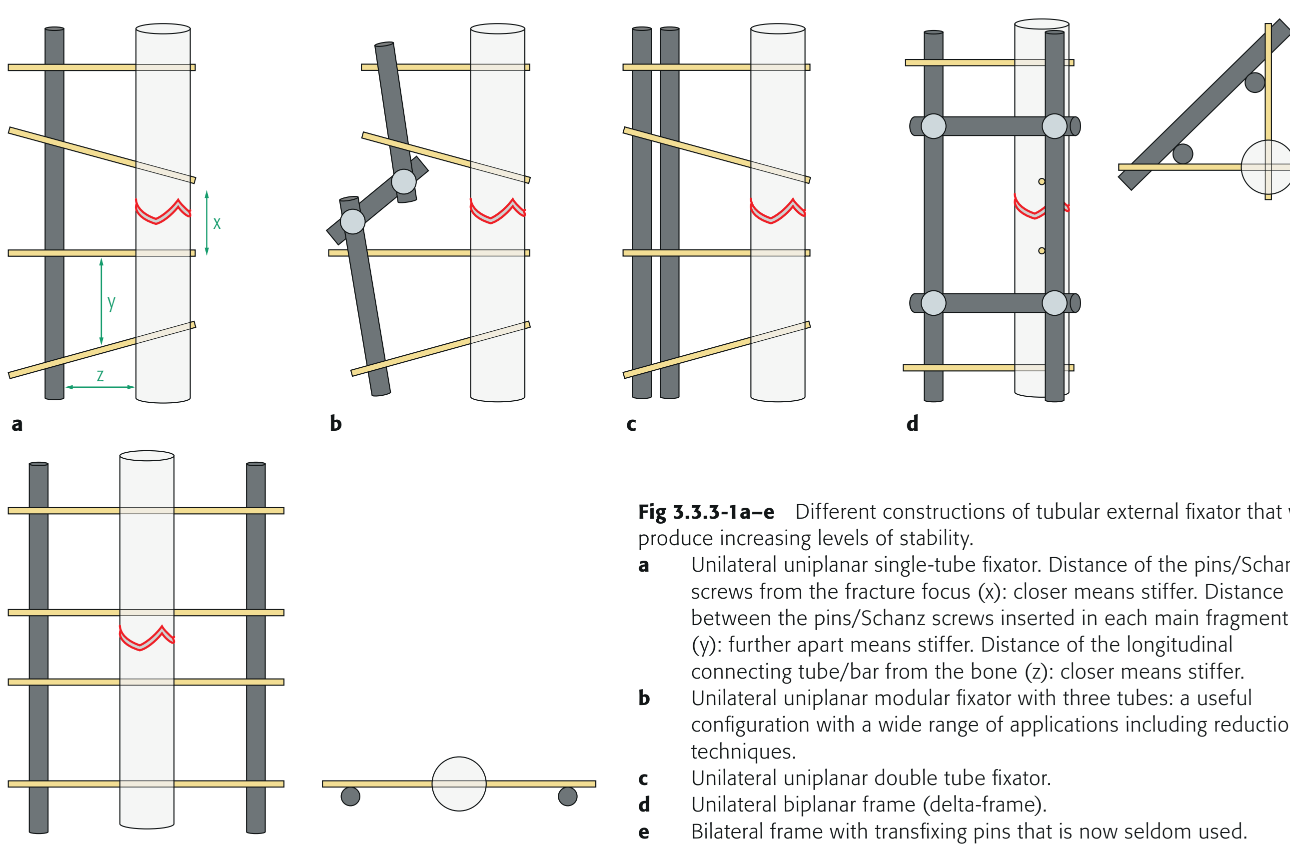


Fig 3.3.3-1a–e Different constructions of tubular external fixator that will produce increasing levels of stability.

- **a** Unilateral uniplanar single-tube fixator. Distance of the pins/Schanz screws from the fracture focus (x): closer means stiffer. Distance between the pins/Schanz screws inserted in each main fragment (y): further apart means stiffer. Distance of the longitudinal connecting tube/bar from the bone (z): closer means stiffer.
- **b** Unilateral uniplanar modular fixator with three tubes: a useful configuration with a wide range of applications including reduction techniques.
- **c** Unilateral uniplanar double tube fixator.
- **d** Unilateral biplanar frame (delta-frame).
- **e** Bilateral frame with transfixing pins that is now seldom used.

3.2.1 Diaphysis

It is essential to avoid thermal damage to the bone when inserting a pin or Schanz screw into hard cortical bone.

The sharper the drill bits or screws, the less heat is generated. The temperature rises as the insertion speed increases. Burning the bone can be a serious problem and may result in early loosening due to ring sequestrum formation and/or infection. A correctly inserted pin or screw should find purchase in the opposite cortex but not protrude too far beyond it.

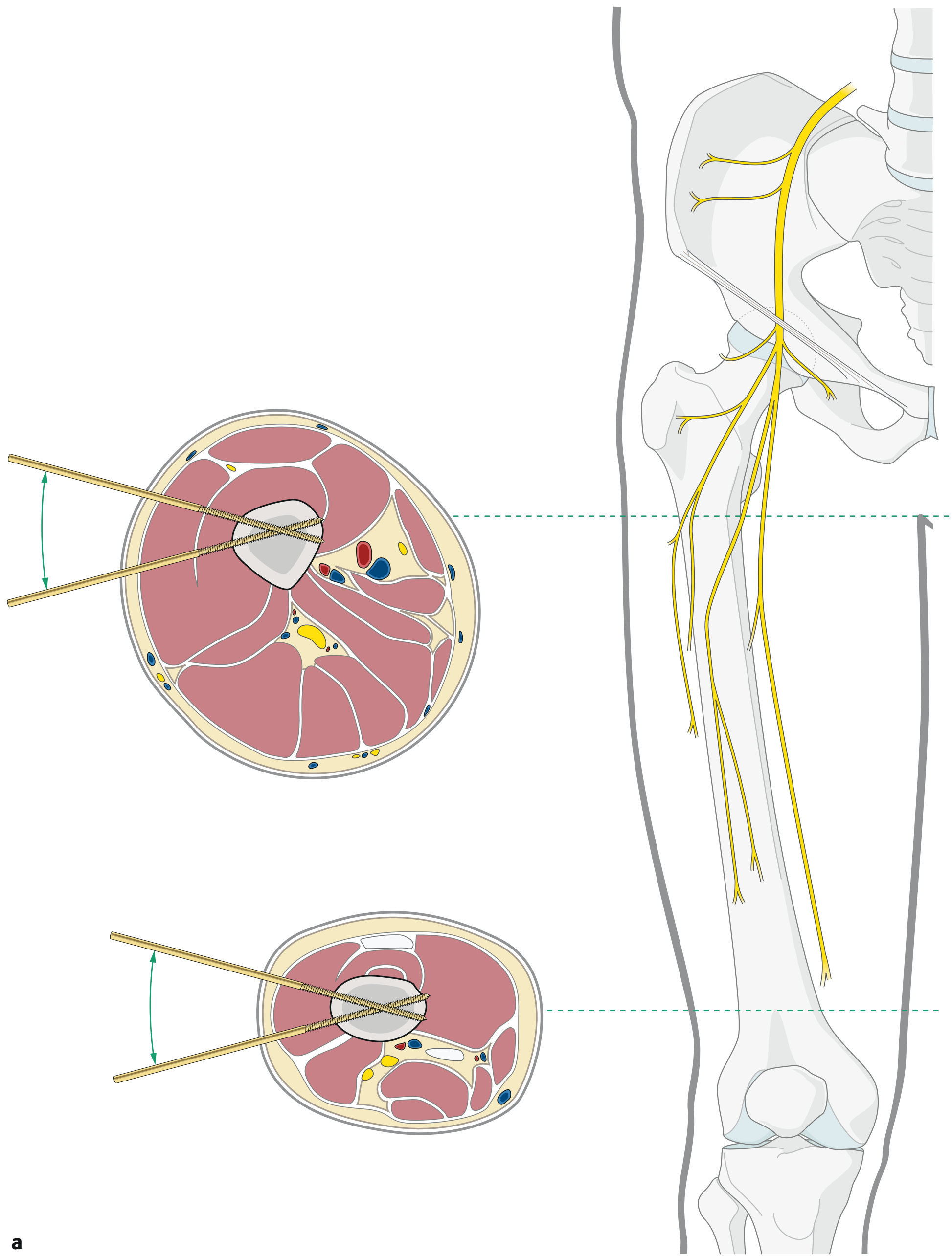
3.2.2 Metaphysis

In metaphyseal bone, heat generation is not such a problem. It may be safer to use self-drilling screws since it is easy to miss the predrilled hole. Joint penetration must be avoided because of the danger of pin-track infection spreading into a joint. The surgeon must be aware of the insertion of the joint capsule.

3.2.3 Safe zones

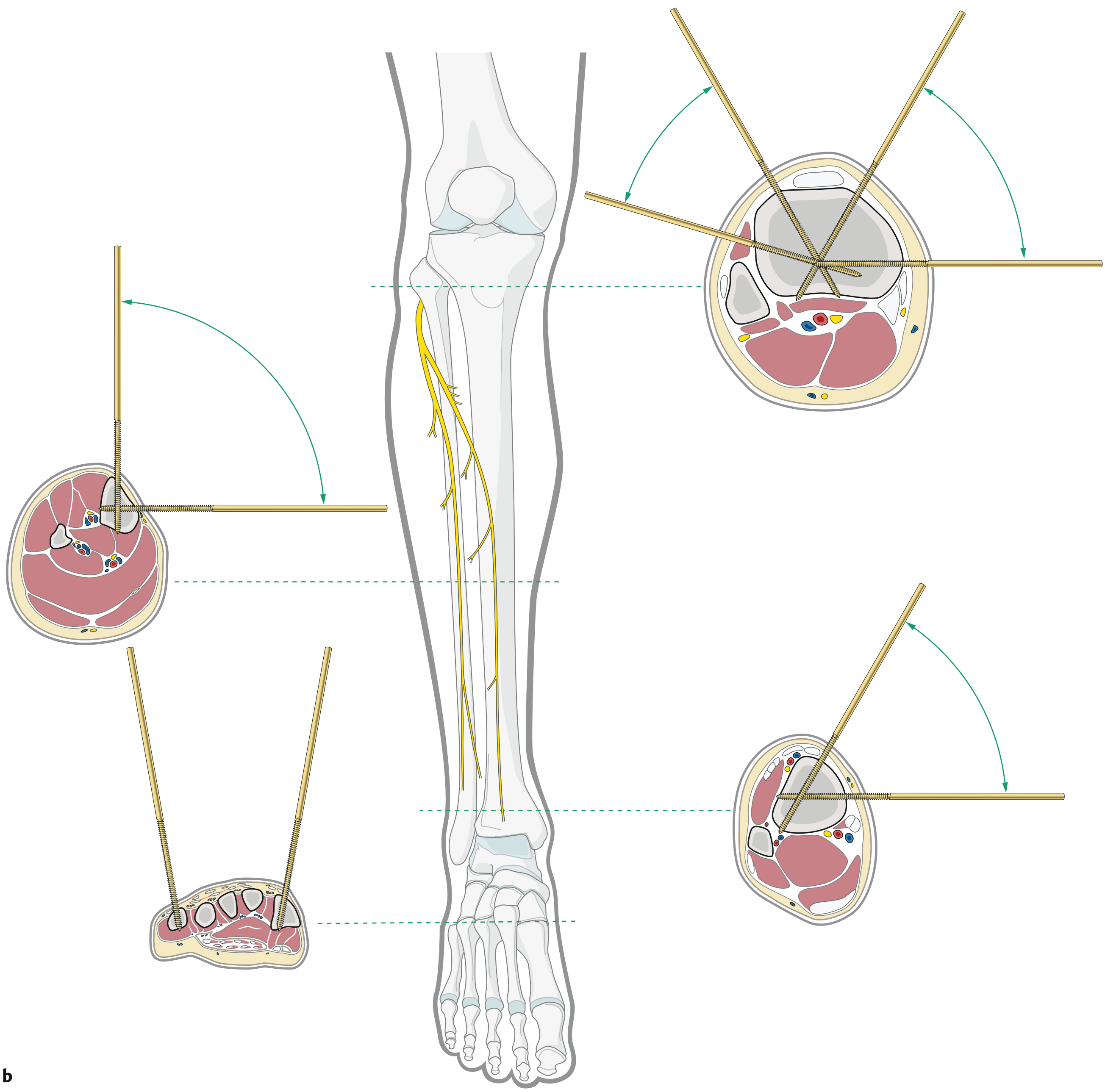
To avoid injuries to nerves, vessels, tendons, and muscles, the surgeon must be familiar with the anatomy of the different cross-sections [8] of the limb and make use of the safe zones for pin placement (**Fig 3.3.3-2**).

In the tibia, it is not necessary to place the Schanz screws at the anterior tibial crest in a uniplanar application. Stability in the tibial crest is high due to the thick cortex. However, excessive purchase in the cortex is usually not required because of the adequate thickness of the anteromedial tibial wall and bicortical anchorage of the Schanz screws. The drilling of a hole in the thick tibial crest may be associated with excessive heat generation and subsequent necrosis of the bone. Insertion of a Schanz screw at the tibial crest may be difficult as the tip of the drill bit may slip medially or laterally, damaging the soft tissues. In the distal tibia, there is a risk of damage to the tendons of the tibialis anterior and extensor digitorum muscles and the most distal pin sites also have the highest infection rate. There is, however, a safe zone on the anteromedial aspect of the tibia, where Schanz screws can remain for a long period without infection.



a

Fig 3.3.3-2a–c Safe zones for insertion of external fixation pins.
a Femur.



b

Fig 3.3.3-2a–c (cont) Safe zones for insertion of external fixation pins.
b Tibia.

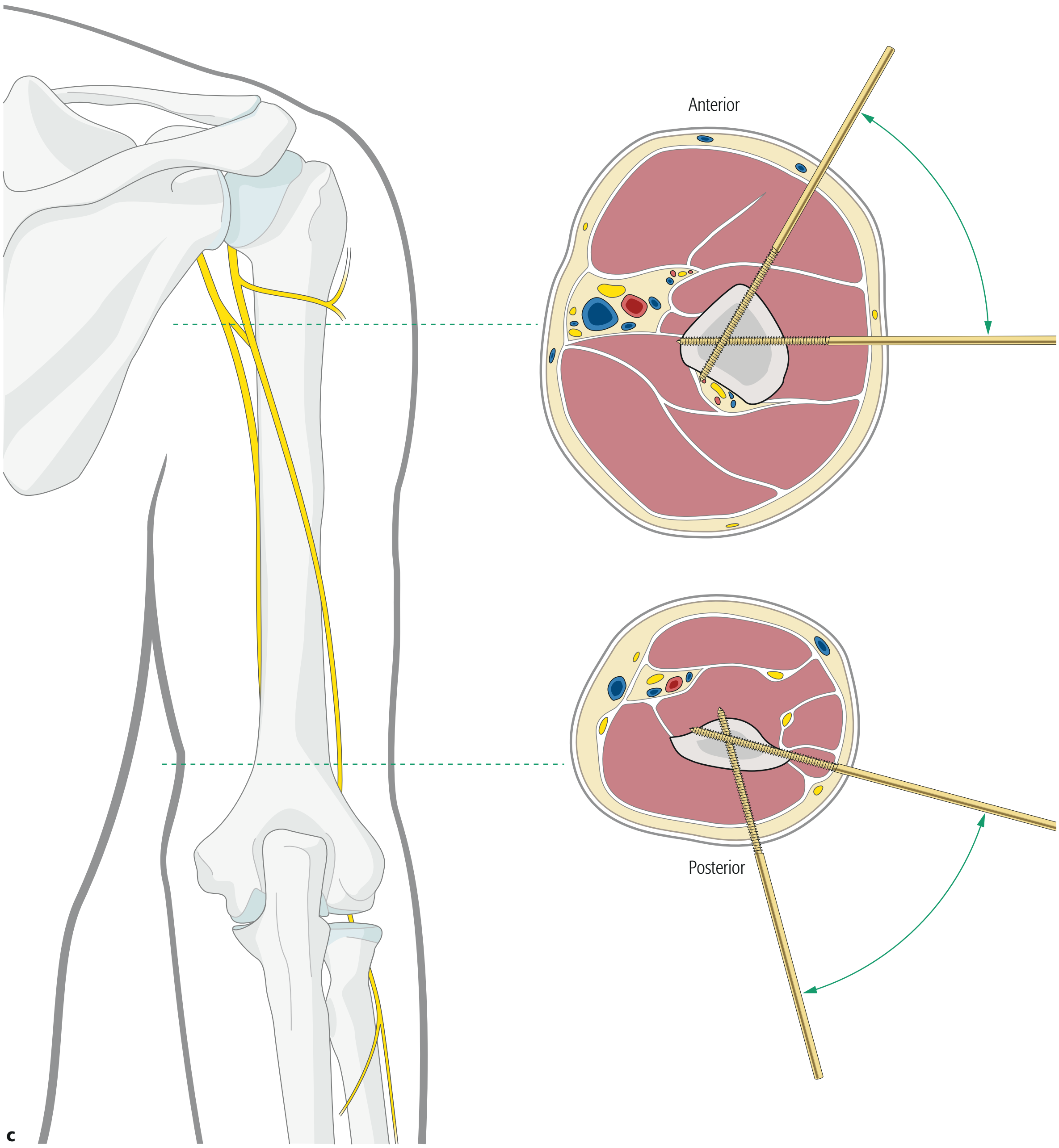


Fig 3.3.3-2a–c (**cont**) Safe zones for insertion of external fixation pins.
c Humerus, posterior view.

4 Elements

4.1 Tube-rod system

4.1.1 Schanz screws

Schanz screws are partially threaded pins. These are available in different diameters and lengths (shaft, threaded part) and with different tips. Standard Schanz screws have trocar-shaped tips (**Fig 3.3.3-3a**). They always require predrilling.

Self-drilling and self-tapping Schanz screws have a sharp and specially designed tip that drills and cuts the thread in one pass: they are designed for use in metaphyseal bone (**Fig 3.3.3-3b**), Schanz screws are available in steel, titanium, or with a hydroxyapatite coating. The hydroxyapatite allows bone growth right up to the pin (osseo-integration) and reduces the incidence of pin loosening. These pins are used in cases where the external fixator is likely to be in place for a prolonged period.

4.1.2 Steinmann pins

Steinmann pins are used as transosseous pins. They have a trocar tip and insertion always requires predrilling in cortical bone.

4.1.3 Rods/tubes

The frames consist of systems in four sizes, depending on the size of the rod (**Fig 3.3.3-4**):

- **Large:** 11 mm tubes/rods with Schanz screws from 4 to 6 mm
- **Medium:** 8 mm tubes/rods with Schanz screws from 3 to 6 mm
- **Small:** 4 mm tubes/rods with Schanz screws from 1.8 to 4 mm
- **Mini:** 2 mm system for fingers; it is presently available in the conventional design and includes multipin clamps for K-wires and 2 mm longitudinal rods

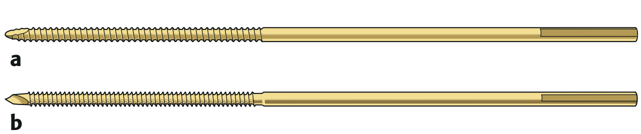


Fig 3.3.3-3a–b Schanz screws.
a Standard trocar tip.
b Self-drilling tip.

These systems are compatible with each other. The large 11 mm system contains both steel tubes and carbon fiber rods. The other systems include carbon fiber rods (medium) or steel and carbon fiber rods (small and mini). The modules of the system are supplemented by precontoured, curved carbon fiber rods. Additional T-shaped combinations are available for difficult regions, such as the wrist.

4.1.4 Clamps

Clamps provide the connection between the tubes or rods and the pins. Rods or tubes can also be connected to each other using the appropriate clamps (tube-to-tube). If a single clamp allows the connection of both tubes and rods, they are called combination clamps. Both single-pin and multipin clamps are available. The newest and most commonly used clamps are illustrated in **Fig 3.3.3-5**. These are available in three sizes with identical clamp design and application technique. The main feature of the new clamp is that it is open on one side and can be “snapped on”. This means that once snapped onto a rod, it can be moved around axially and laterally without the need to be tightened. This greatly facilitates handling, especially for the modular reduction technique. The configurations described later in this chapter can also be constructed with other clamps that have similar functions or with older models.

Fig 3.3.3-4 Stainless steel tubes and carbon fiber rods for the large (11 mm) system.

4.2 Monolateral external fixation system

This is a system for traumatology and orthopedics (**Fig 3.3.3-6**), where the bone fragments are held by twin-pin clamps or special clamps. A central body for distraction and compression or a central-threaded component can be attached for lengthening and/or segmental transport procedures.

4.3 Hybrid external fixator

The hybrid external fixator is used in fractures close to a joint. It is called "hybrid" because it combines tensioned fine-wire fixation and an external ring at the joint with pin fixation in the diaphysis (**Fig 3.3.3-7**). It requires tensioned K-wires for the ring and conventional Schanz screws for the shaft. Generally, 3/4 circumference rings are used. Hybrid ring fixators have mainly been used in proximal and distal tibial fractures (**Video 3.3.3-2**).

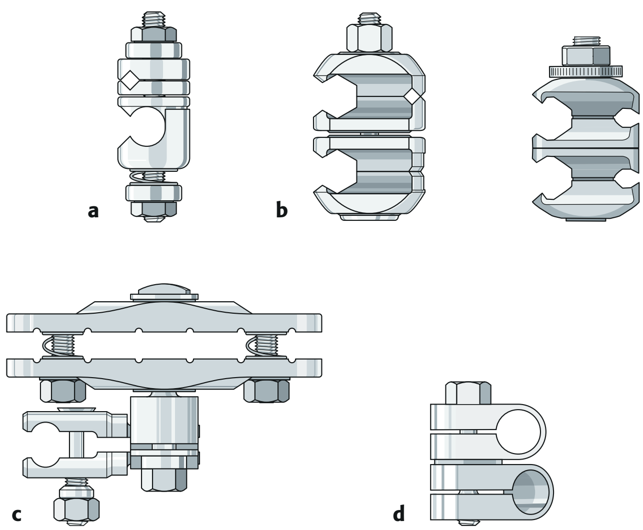


Fig 3.3.3-5a–d Clamps.
- **a** Attachable, self-holding clamp used for combining a Schanz screw with a tube or rod.
- **b** Attachable combination clamp used for combining two rods or tubes or Schanz screws.
- **c** Universal multipin clamp.
- **d** Closed tube-to-tube clamp used for combining two rods or tubes.

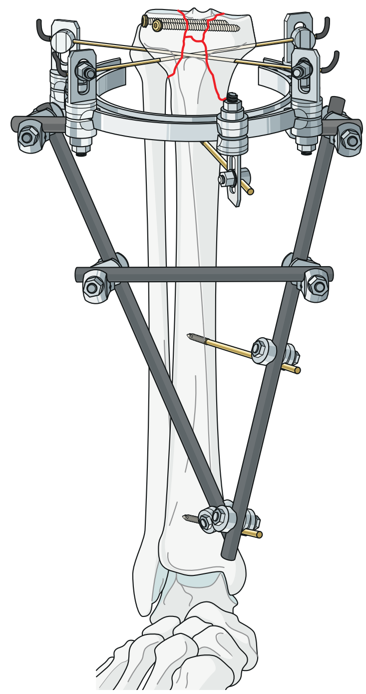


Fig 3.3.3-7 Hybrid fixator used on a tibial plateau fracture. It is also useful for distal tibial periarticular fractures. The V-frame provides good stability.

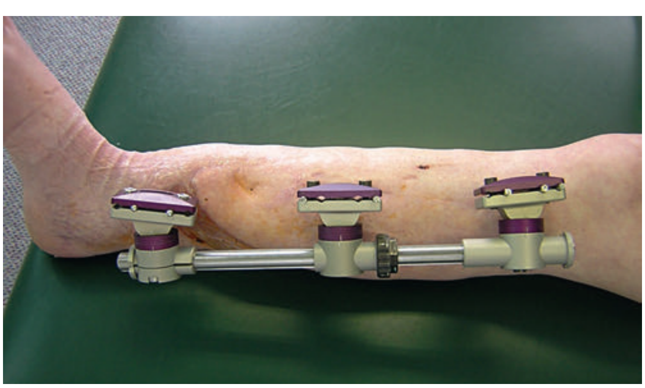
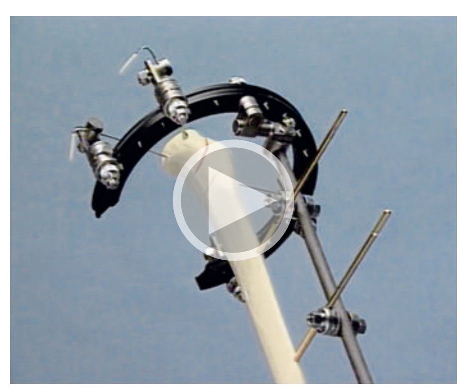


Fig 3.3.3-6 Monolateral external fixation system for segment transport on the tibia.



Video 3.3.3-2 Application of the hybrid fixator. Tensioning of a fine wire.

4.4 Circular ring fixator

Full ring systems offer the advantage that the axis of loading and the axis of correction simultaneously pass through the center of the ring system and on the longitudinal axis of the bone [9]. Lengthening, segment transport, simple, and especially complex fracture treatment is possible with circular ring systems (**Figs 3.3.3-8–9**) and this technique allows for early weight-bearing. For the treatment of acute fractures we prefer simpler unilateral methods. Segment transport and lengthening procedures are possible with unilateral systems but complex continuous correction in several planes is difficult to achieve, so a circular ring fixator is recommended.

As the ring fixator is an external fixator, it provides relative stability. When pins are inserted across different planes in multiplanar fixation, the construct provides great stability. The stiffness of the construction can vary depending on the configuration of the fixation, the number of rings used, and usage of different types of pins, such as K-wires or Schanz screws. Depending on the assembly, the fracture can be distracted or compressed, and deformities can be corrected. A common use for the ring fixator is distraction osteogenesis to correct bone loss, shortening, and deformity.

An enhancement for patient care is the connection of rings with a hexapod system. A computer program calculates movement of the six oblique bars to allow reduction of any malalignment. The indications for ring and hexapod systems are specialized. For more information on ring and hexapod systems, specialized textbooks and teaching material are available.

4.5 Hinged external fixator

Hinged external fixators maintain reduction of joint dislocations or fracture dislocation and allow some (controlled) motion at the joint to help prevent joint stiffness. They are most commonly used in the elbow (see section 6.5 in this chapter).

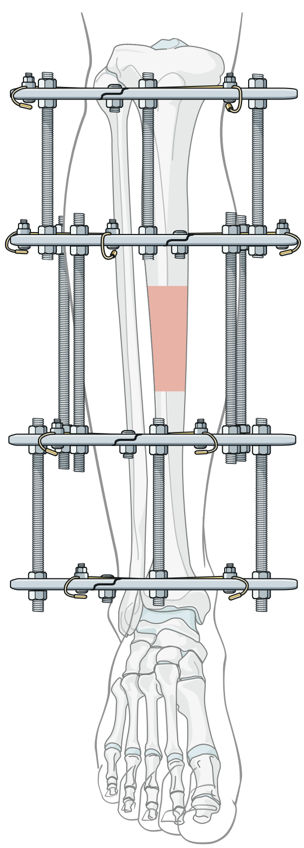


Fig 3.3.3-8 A circular frame on the tibia

Fig 3.3.3-9 Clinical photo of a ring system on the tibia.

5 Frame construction

5.1 Terminology of frame construction

There are different ways to classify a frame construction, depending upon:

- Function
- Design
- Plane in which it is applied
- Indication

5.1.1 Unilateral frame

A unilateral frame is the most common way to stabilize fresh diaphyseal fractures with an external fixator.

The frame is applied in one plane, ie, either anteromedial or medial for the tibia and anterolateral or lateral for the femur (**Fig 3.3.3-1c**). The pins are placed through the skin on one side and penetrate both the near and far cortex. Pins must be inserted away from the joints and be outside the joint capsule reflections to avoid the risk of joint sepsis. Two bars are mounted, either both in one plane or in two different planes, and joined together.

5.1.2 Bilateral frame or A frame

A Steinmann pin is inserted through the skin on one side, penetrates both cortices, and emerges through the skin on the opposite side. It is not recommended for the definitive treatment of fractures but can be a useful temporary fixation.

5.1.3 Spanning external fixation frame (joint bridging)

Spanning external fixation is indicated for damage-control surgery when the patient (polytrauma), or the limb, or the fracture cannot be definitively managed immediately.

It is used to span areas of severe soft-tissue injury or complex articular fractures and fracture dislocations (**Fig 3.3.3-10**). The stability allows time for soft tissues to settle, while computed tomographic (CT) scans and preoperative planning are performed. Unilateral frames are mostly used and the pins should be placed where possible outside the zone of injury and outside the zone of (future) definitive surgery.

5.1.4 Lengthening frame

The external fixator can be modified to allow for distraction osteogenesis. Ilizarov introduced this technique with the ring fixator. The same principle of slow distraction can be applied with the tubular external fixator and monolateral systems with the limitation that angular and rotational corrections cannot be performed simultaneously unless lengthening is performed over an intramedullary nail.

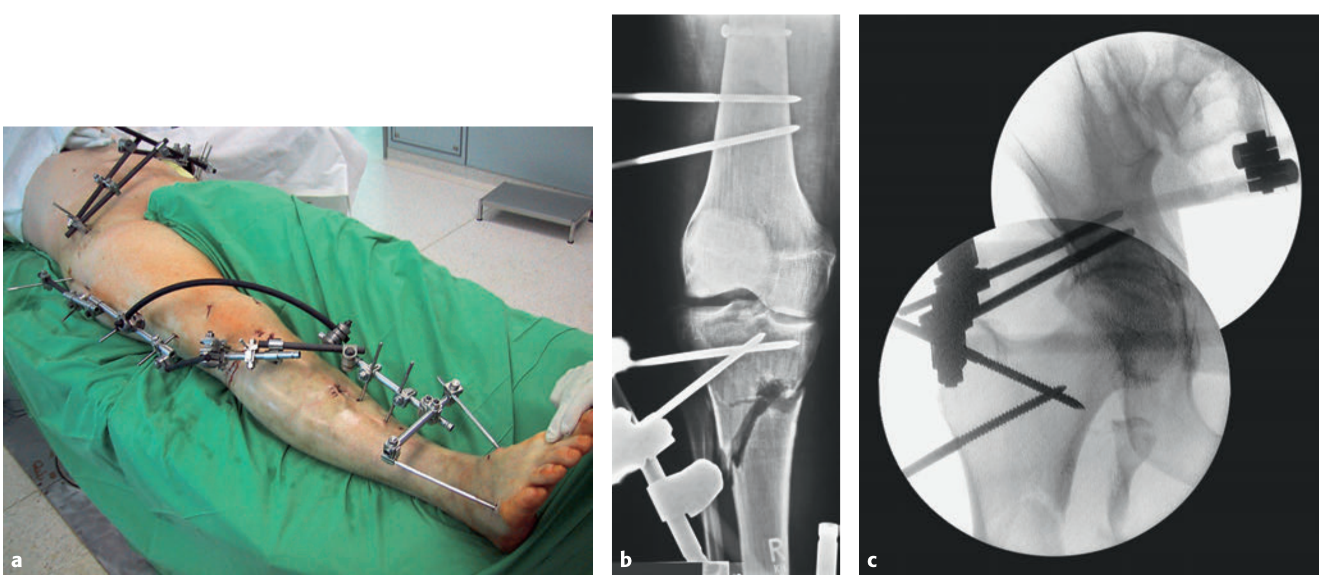


Fig 3.3.3-10a–c Fractures of the pelvic ring, proximal femur, and proximal tibia, all fixed with temporary external fixators, bridging the knee and ankle joints.

5.2 Modular reduction technique

The modularity of the external fixator makes it versatile and allows it to be used both as an indirect reduction tool and fixation device.

5.2.1 The principle

Schanz screws are inserted into each main fragment with the pin close to the fracture placed in slightly different plane or, in the case of joint-bridging configurations, into each of the two bones supporting the bridge (in some cases possibly more than two) (**Fig 3.3.3-11**) [10].

If single pin clamps are used, there is a great advantage that the position and orientation of the Schanz screws are unrestricted.

The Schanz screws within one fragment are then firmly connected to a tube or rod. This produces a partial frame for each main fragment/affected bone. The two partial frames are then connected by means of tube-to-tube clamps. As long as the tube-to-tube connections are open, reduction can be performed in all planes. The desired reduction, once achieved, can be checked clinically and/or radiologically, the tube-to-tube clamps can be tightened and the system is stable (**Videos 3.3.3-3–4** and **Fig/Animation 3.3.3-12a–c**)

5.2.2 Modifications

The two Schanz screws in any one main fragment can be held in place by double pin or multipin clamps. These double or multipin clamps can be applied on one side or on both sides of the fracture. The partial frame can also be formed by a ring or a partial ring system (hybrid fixator).

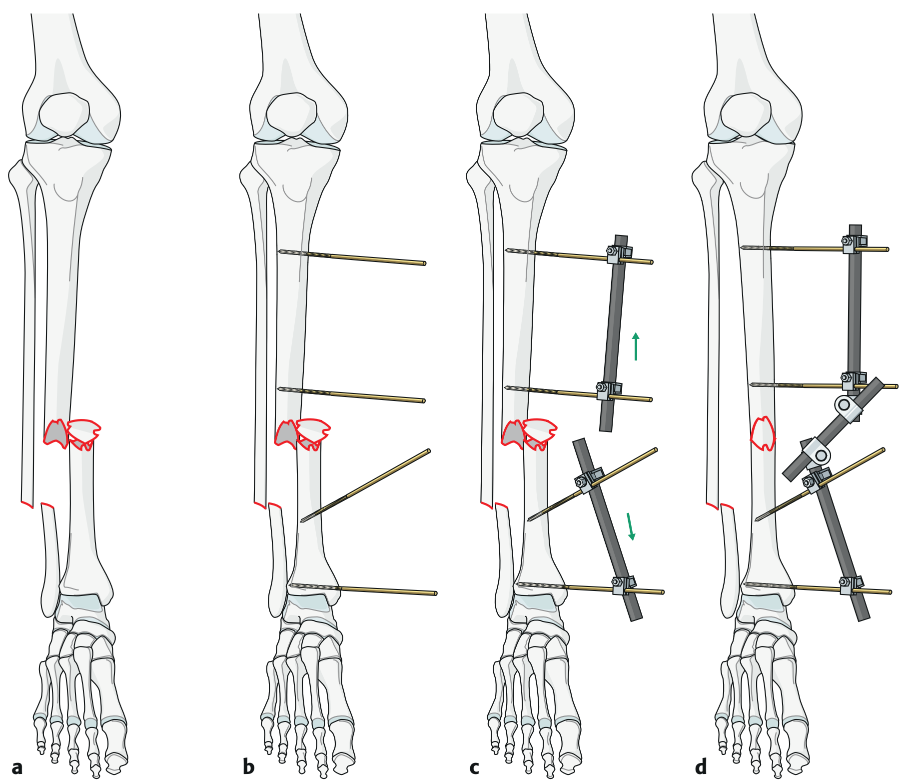


Fig 3.3.3-11a–d The modular reduction technique.
a Type B diaphyseal tibial fracture.
b Two pins are inserted in each main fragment outside the zone of injury.
c Fixed to a bar by universal clamps, two handles are created that help reduction.
d After reduction the tube-to-tube clamps of the third tube are tightened.

5.2.3 Advantages

The advantage of modular external fixation is that all long bones, areas adjacent to joints, and the joints themselves (joint bridging) can be reduced, bridged, and stabilized.

The Schanz screws can be positioned freely, which allows the most favorable, anatomical insertion site for the Schanz screws and the most favorable zone for the fracture pattern or soft-tissue injury. Manipulation of the main fragments is facilitated by leverage and indirect reduction techniques which preserve bone and soft-tissue vascularity. Primary and secondary adjustments to the reduction can be performed at any time with this technique.

6 Special applications

6.1 Arthrodesis

One of the special applications of external fixation has always been the fusion of a joint by applying compression through a bilateral frame. This principle is occasionally used for ankle, knee, and elbow fusion, especially in the presence of infection [11]. The threaded rod system or the removable compression device for the tubular system allows for repeated application of axial compression, which increases stability in the less dense bone of the metaphysis.

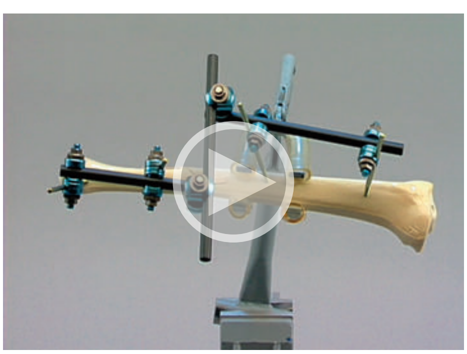
6.2 Infection

External fixation may be the ultimate way of stabilizing an acutely infected fracture or infected nonunion because the fixation pins can usually be inserted distant from the focus of infection.

External fixation may be the only method that can provide stability, which is essential for successful treatment in this situation. After debridement and removal of all dead bone and necrotic tissue, the techniques for application of the external fixator are essentially the same as for fresh fractures.

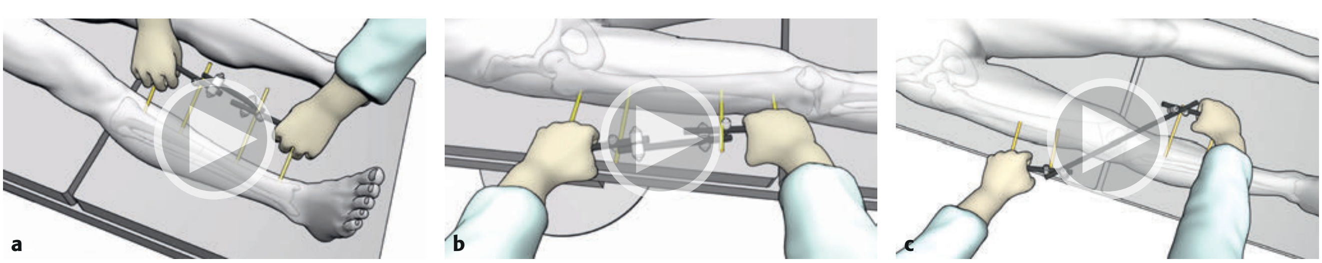
6.3 Corrective osteotomies

External fixation of osteotomies for deformity correction is generally used in cases of poor or compromised soft-tissue cover, ie, when internal fixation is associated with high risk (see chapter 5.2). The other indication is for osteotomies combined with bone transport.



Video 3.3.3-3 Modular external fixation of the tibia.

Video 3.3.3-4 Modular external fixator on a tibia with soft-tissue damage around the knee joint. Final treatment of a tibial fracture shown preoperatively, operative technique and after treatment with external fixator and healing with external fixator treatment.



Fig/Animation 3.3.3-12a–c Modular external fixator shown with:
a Tibia.
b Femur.
c Knee bridging.

The combination of poor soft tissues and a complex deformity will usually need correction using a circular frame system.

6.4 Bone transport—distraction osteogenesis

Callus distraction is based on the principle described by Ilizarov [9]. By preserving the periosteum, carefully osteotomized bone can slowly be distracted (0.5–1 mm/day) and new bone will form in the gap. Slower rates of distraction result in bone healing while faster rates exceed the strain tolerance of the tissue and bone does not form. Transport or distraction callus, like fracture callus, passes through all phases of maturation until complete bone union is achieved. This principle can be used for three indications, which may occur in combination:

- Lengthening
- Segment transport into a defect
- Correction osteotomy

The fixators best suited to these applications are the ring fixators with or without combinations of partial rings as well as unilateral fixators.

6.5 Joint reduction and maintaining motion

Hinged external fixation is an important supplement to ORIF and ligament repair for selected complex unstable elbow injuries, including the chronic or unreduced elbow dislocation. When surgical repair does not provide adequate stability, redislocation or subluxation may occur with or without a cast or splint. External fixation with a hinged device will keep the elbow reduced while allowing controlled motion. Maintenance of reduction is the first priority. Instability is harder to salvage than loss of motion. Axis wire location should be determined precisely, using the image intensifier. Slight misplacement of the hinge significantly affects hinge behavior (**Fig 3.3.3-13**).

7 Postoperative management

7.1 Pin-track care

The reaction at the pin insertion site depends upon the position and stability of the pin [12] and aftercare by the nursing team and patient.

The modular reduction technique is favorable from this point of view because it permits the best anatomical site to be selected in relation to the fracture pattern [10]. If there is a "steady state" at the pin-insertion site, without signs of infection, the external fixator can be left in place for a long time.

It is important that hospitals have clear protocols for the management of pin sites with experienced nurses teaching patients to take care of the pin sites on their own.

Infection and loosening of pins can be significantly reduced by avoiding thermal damage and local hematoma formation during insertion and if after-care includes the use of alcoholic antiseptic to clean the pin sites together with occlusive pressure dressings [13]

7.2 Pin-track infection

Pin-track care starts with correct pin insertion. Predrilling is always recommended for the conventional Schanz screw and the pin should always be inserted by hand to reduce thermal necrosis. Undue soft-tissue tension around the pins

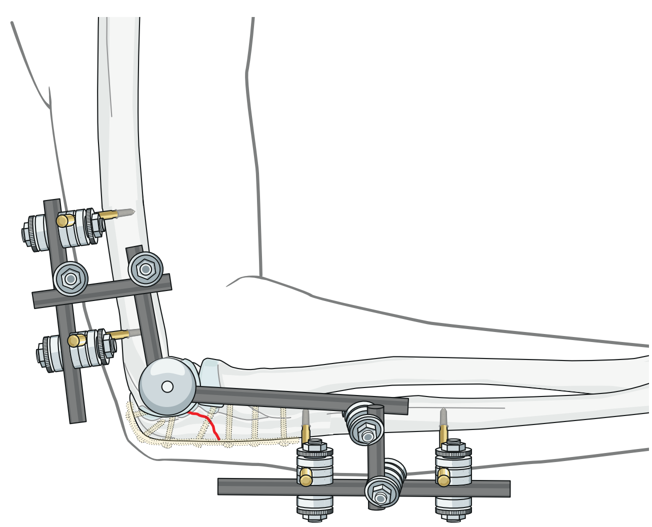


Fig 3.3.3-13 Placement of hinged elbow external fixator.

must be released during surgery. Correct care of the pin-track sites is important to reduce the risk of pin-track complications. In cases of persistent pin-track infection, the pin has usually lost its firm hold in the bone. A seam of bone resorption can be seen on the x-rays and mechanically the pin appears to be loose. This problem can be solved by removing the loose pin and placing a new one at another site.

7.3 Dynamization

With a few exceptions (bridging, emergencies, tensioning), external fixator constructs can be partially loaded from the beginning. As healing progresses, the load is increased until full weight bearing is achieved. Observations over many years have shown that it is not necessary to build additional dynamization elements into the fixator system. Partial and full weight bearing under external fixation is the best and most effective method of dynamization.

8 For how long should the external fixator be used?

8.1 Change of procedure

There are three basic treatment choices:

- Definitive treatment with the external fixator until solid bone healing
- Early conversion to internal fixation
- Conversion to nonoperative treatment, eg, plaster, orthosis, caliper

If a change to internal fixation is predicated, this must be done early—within 2 weeks—as this results in a remarkably lower complication rate than a change at a later stage.

Any surgery that is planned around or after temporary external fixation must follow a few rules:

1. All pin sites must be clean if new internal fixation is placed around old sites of external fixation. Sometimes this requires 2-stage surgical procedures to first clean the old pin sites followed by the definitive fixation procedure.
2. Any pin sites more than 10–14 days are assumed to be colonized and should go through a sterile cleaning and debridement procedure before definitive fixation is placed near these sites.
3. If there is any doubt about the sterility of these pin sites, or if they have been frankly infected, then a "pin holiday" of at least 10 days is used after a sterile debridement procedure before placing new internal fixation.
4. Prophylactic antibiotics must be administered and cover the bacteria responsible for any previous pin-site infections.
5. Close postoperative follow-up is performed during the first 6 weeks.

If there is evidence of pin-track problems, it may be best to identify the organism, administer antibiotics, make a change of pin and pin site, and continue treatment using an external fixator. Pin-site care should be reviewed with the patient to ensure that it is optimal. If late removal of the fixator and change to internal fixation is necessary, a "pin holiday" is recommended. This means that the external fixator is removed, the pin sites cleaned and debrided and the limb is then immobilized in a splint; surgery is delayed until the pin sites have settled. Appropriate antibiotics are administered.

8.2 Definitive fixation

The initial emergency application of an external fixator establishes temporary stabilization of a limb, allowing the soft tissues to recover. As soon as the soft tissues appear stable, the external fixator can be replaced by a definitive internal fixation. Ideally, this should take place within 10 days. A conversion procedure is not mandatory if the frame is still stable and there are no signs of complications

In cases of poor skin coverage or critical soft-tissue concerns, open reduction will be associated with a high risk of infection. Therefore, the external fixator may be retained as the definitive fracture treatment.

The progress of fracture healing must be monitored carefully and if there is no progress an alternative approach should be considered.

Classic references | Review references

9 References

1. **Perren S.** Basic aspects of internal fixation. In: Müller ME, Allgöwer M, Schneider R, eds. *Manual of Internal Fixation*. Berlin Heidelberg New York: Springer-Verlag; 1990:1–112.
2. **Pape HC, Krettek C.** [Damage control orthopedic surgery]. *Unfallchirurg.* 2003 Feb; 106(2):85–86. German.
3. **Giannoudis PV.** Surgical priorities in damage control in polytrauma. *J Bone Joint Surg Br.* 2003 May; 85(4):478–483.
4. **Jakob RP, Fernandez DL.** The treatment of wrist fractures with the small AO external fixation device. In: Uhthoff HK, ed. *Current Concepts of External Fixation of Fractures.* Berlin Heidelberg New York: Springer-Verlag; 1982; 307–314.
5. **Fernandez DL.** Treatment of articular fractures of the distal radius with external fixation and pinning. In: Saffar P, Cooney WP, eds. *Fractures of the Distal Radius.* London: Martin Dunitz Ltd; 104–117.
6. **Schütz M, Müller M, Regazzoni P, et al.** Use of the less invasive stabilization system (LISS) in patients with distal femoral (AO 33) fractures: a prospective multicenter study. *Arch Orthop Trauma Surg.* 2005 Mar; 125(2):102–108.
7. **Lazo-Zbikowski J, Aguilar F, Mozo F, et al.** Biocompression external fixation. Sliding external osteosynthesis. *Clin Orthop Relat Res.* 1986 May; (206):169–184.
8. **Faure C, Merloz PH.** *Zugänge für die Fixatuer-externe-Osteosynthese. Atlas anatomischer Querschnitte.* Berlin Heidelberg New York: Springer-Verlag; 1987. German.
9. **Ilizarov GA.** [Basic principles of transosseous compression and distraction osteosynthesis]. *Ortop Travmatol Protez.* 1971 Nov;32(11):7–15. Russian.
10. **Fernandez Dell'Oca AA.** External fixation using simple pin fixators. *Injury.* 1992;23 Suppl 4:S1–54.
11. **Mears D.** Clinical techniques in the lower extremity. In: Mears D, ed. *External Skeletal Fixation.* Baltimore London: Williams & Wilkins; 1983; 210–338.
12. **Green S.** Complications of external fixation. In: Uhthoff HK ed. *Current Concepts of External Fixation of Fractures.* Berlin Heidelberg New York: Springer-Verlag; 1982.
13. **Davies R, Holt N, Nayagam S.** The care of pin sites with external fixation. *J Bone Joint Surg Br.* 2005 May; 87(5):716–719.

10 Acknowledgment

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3.3.4 Locking plates

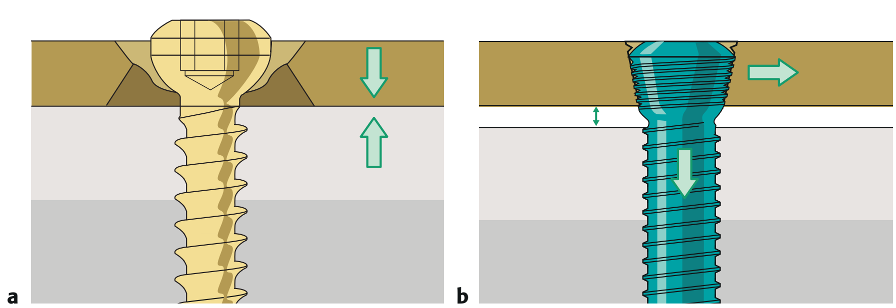
Christoph Sommer

1 Introduction

The introduction of locking plates was driven by the aim of maximizing blood supply to the fracture. When using conventional plates and screws, the stability of the bone-implant construct is dependent upon friction between the plate and the bone. This can only be achieved by pressing a plate down onto the bone surface by tightening conventional screws.

Considerable structural changes occur in the cortex directly underneath a plate. These changes were first attributed to "stress protection" by a metallic implant that was much more rigid than bone. Further research [1, 2] gave rise to the theory that disturbed blood flow within the cortical bone was responsible for the remodeling process observed underneath every plate that was pressed against bone by screws.

The under surface of the limited-contact dynamic compression plate (LC-DCP) was designed to reduce the area of contact between the plate and bone and significantly reduced the vascular changes caused by pressure on the cortex. However, the LC-DCP is also pressed against the bone to create friction (**Fig/Animation 3.3.4-1a**). To eliminate the ill effects of any plate to bone contact, a completely different approach was chosen. Screws that rigidly lock into the plate hole when tightened mean that the plate is no longer pressed against the underlying bone (**Fig/Animation 3.3.4-1b**) [3]. Similar in principle to the external fixator, this different technique of applying a plate was termed the internal fixator principle, as the implant functions more like a fixator than a plate with soft tissues and skin covering the whole construct. Since these devices are designed to avoid the devascularization associated with conventional plating, theoretically, they should offer higher resistance to infection. However, this hypothesis has not been proven.



Fig/Animation 3.3.4-1a–b The plate-bone interface.
a Conventional plates gain stability by friction as the screw presses the plate against the cortex. The periosteum is crushed, resulting in avascular areas.
b Locking head screws mechanically couple to the plate, which is not pressed against the bone. The periosteum and blood supply are therefore maintained.

The history of the development of locking plate technology is illustrated in **Fig 3.3.4-2**.

The concept of locking plates is not new and the first known patent was in 1931 by the French surgeon, Paul Reinhold. The first modern implant designed to fulfil the new requirements was the small PC-Fix (point contact fixator) for forearm bones. The PC-Fix was a narrow plate-like implant with a specially designed under surface having only small points that come into contact with bone. The screws were self-tapping, unicortical and were available in one length only. The conical screw head locked firmly in the corresponding conical plate hole when tightened. The result of further developments was the less invasive stabilization system (LISS) [4]. This implant, in contrast to the PC-Fix, was conceived for fractures in the metaphyseal areas—initially for the distal femur and later for the proximal tibia. Its shape conforms to the anatomical contours of the specific area of the bone and so separate implants are required for the right and left sides. Additional contouring is not required, as the "plate" fixator does not necessarily need to touch the bone. The locking head screws (LHS) have a conical head with a fine thread, fitting perfectly in the corresponding threaded conical plate hole. The stability achieved using LHS relied on a stable couple between screw head and plate hole, and was not dependent on the friction between the plate and the bone (**Fig/Animation 3.3.4-1**). Initially the system consisted of unicortical, self-drilling/self-tapping screws, which are inserted percutaneously using an aiming arm. However, failure rates were high in clinical application and bicortical, self-tapping screws are now recommended. This implant was designed and instrumented for application via a minimally invasive, submuscular approach.

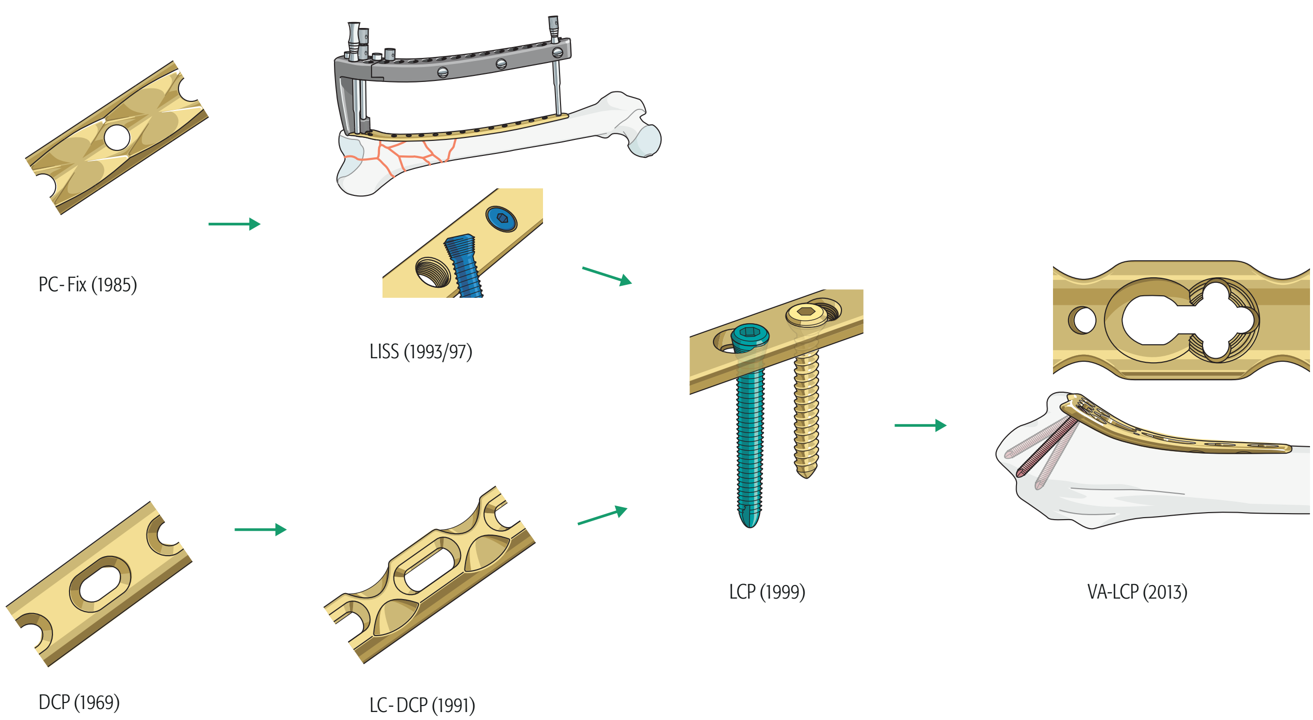
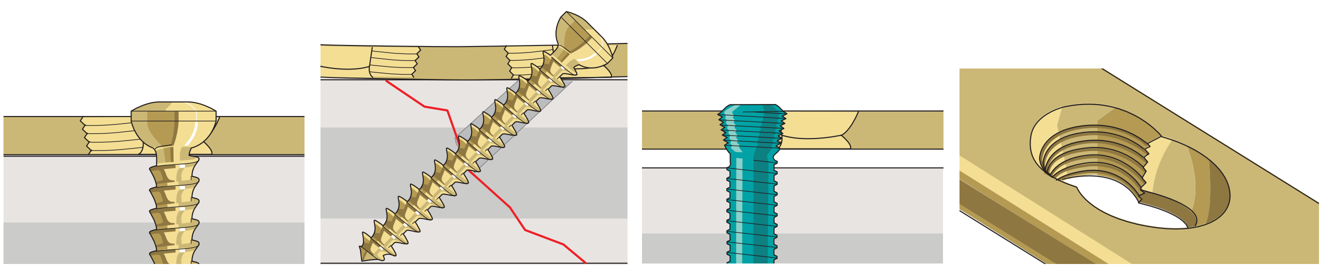


Fig 3.3.4-2 The evolution of plate systems.
Conventional plate development in the 1960s to 1980s was followed by locking plate development in the 1990s until they were integrated to produce the locking compression plate (LCP). The latest step was the introduction of variable angle (VA) technology.

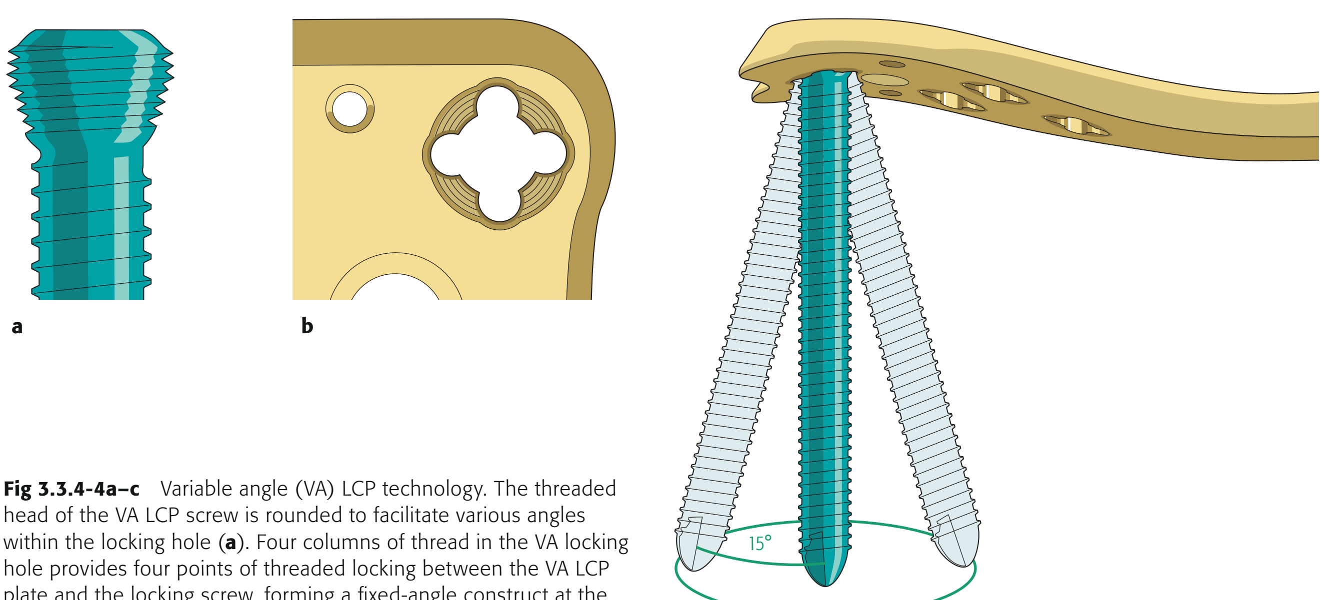
The locking compression plate (LCP) was developed in 1999. This implant is a combination of the LC-DCP and LISS [5, 6]. The holes of both plates have been “fused” into a combination hole (combi-hole), allowing insertion of either conventional or locking screws (**Fig 3.3.4-3**). Within a few years, this LCP technology was implemented in existing plates from the large to the mini-fragment sets, replacing the old dynamic compression unit holes with the new LCP combination holes. Globally, surgeons became familiar with this new technology and its advantages as well as disadvantages [7].

The most recent development is variable angle (VA) technology (**Fig 3.3.4-4**). The spherical head together with the specially slotted plate hole allows angulation of the screw direction (maximal 15°) in relation to the normal 90° (perpendicular) angle to the plate surface. The holding strength of the VA screw in the plate hole is about 70% of the non-VA LHS, but still strong enough to achieve stability when guidelines for application are followed.



a **b** **c** **d**

Fig 3.3.4-3a–d Locking compression plate combination hole combining two proven elements:
a–b Half of the hole has the design of the standard DCP/LC-DCP (dynamic compression unit: DCU) for conventional screws (including lag screws).
c–d The other half is conical and threaded to accept the matching thread of the locking head screw to provide angular stability.



a **b** **c**

Fig 3.3.4-4a–c Variable angle (VA) LCP technology. The threaded head of the VA LCP screw is rounded to facilitate various angles within the locking hole (**a**). Four columns of thread in the VA locking hole provides four points of threaded locking between the VA LCP plate and the locking screw, forming a fixed-angle construct at the desired screw angle (**b–c**).

2 Indications

2.1 General considerations

The essential difference between a conventional plate and a locking plate is not in the plate itself but in the fact that the screws are locked into the plate, therefore the plate and screws together act as one unit.

This means that the construct is less dependent upon the interface between the screw threads and the bone. Thus, there are two key situations where a locking plate should provide a considerable advantage over a conventional plate: poor bone quality, such as found with osteoporosis; and situations where the morphology of the fracture reduces the amount of bone available for fixation (**Table 3.3.4-1**). The classic example is multifragmentary metaphyseal fractures close to the joint surface.

2.2 Poor bone stock

The most important indication for using locking screws is poor bone stock.

Fractures in osteoporotic (or pathological) bone: In poor bone, a conventional screw can easily be overtightened during insertion, damaging the thread hole so the screw gets poor purchase. This may result in early, or even primary, fracture instability (**Fig 3.3.4-5**). The thinner cortical bone in older adults also offers low resistance to pull out and toggle even if initial fixation is obtained. Conventional plating has a higher failure rate in osteoporotic bone, classically seen with sequential screw loosening and migration (**Figs 3.3.4-6–7**, **Videos 3.3.4-1–2**). In contrast, a locking screw can never be overtightened in the bone because of the automatic stop by the locking process at the end of the screw insertion. Locking plates by definition cannot fail on the individual screw–bone interface level (**Fig 3.3.4-8**, **Videos 3.3.4-3–4**); all screws have to pull out together with the plate (**Fig 3.3.4-9**).

Indications	Disadvantages of conventional screws (plates)	Advantages of locking screws	Positive effect using locking screws
Osteoporotic bone (or pathological bone, eg, in revision surgery)	Easy overtightening during insertion which destroys the thread in the bone.	Overtightening (in the bone) is not possible due to locking mechanism, even when overtightened in the plate hole, which is avoided by using the TLA and correct technique.	Reduced risk of primary loss of reduction.
	Easy screw loosening under load (axial, bending, or torsional) before fracture has healed.	Screw loosening in plate hole unlikely if properly placed (correct 90°angle, TLA).	Reduced risk of secondary loss of reduction.
Metaphyseal fracture	Can angulate easily in the plate holes even in good bone quality.	LHS cannot angulate in plate hole. Screws act like multiple small "blades" of an angled blade plate.	Reduced risk of secondary loss of reduction (angulation).
	Short end segment of bone with a short plate creates a short lever arm. Conventional screws cannot withstand high pull-out or bending forces. High risk of sequential screw loosening and migration.	Locking plates by definition cannot fail on the individual screw–bone interface level. All screws have to pull-out together and with the plate.	Reduced risk of secondary loss of reduction with instability.
	Conventional screws do not perfectly fit anatomically preshaped periarticular plates and sufficient plate-bone contact is not achieved.	Stability of fixation does not rely on a perfect fit of the plate to the bone and therefore, using locking screws in preshaped plates, the stability is sufficient.	Perfect primary stability, reduced risk of secondary loss of stability.
Minimally invasive plate osteosynthesis	Bone is pulled to the plate creating malalignment (angulation or torsion) if the plate is not precisely contoured to the bone surface (not possible because surface is not visualized).	Well-reduced fracture stays reduced when using locked screws (distance between plate and bone does not change).	Reduced risk of primary loss of reduction.
Periprosthetic fracture	Monocortical application not sufficient.	Monocortical screws can be added.	Reduced risk of secondary loss of reduction.
	Conventional plates cannot be combined with locking attachment plate or wire-holding buttons.	Combination with locking attachment plate or wire holding buttons possible.	

Table 3.3.4-1 Indications for the use of locking screws and the clinical rational.
Abbreviations: LHS, locking head screw; TLA, torque-limiting attachment.

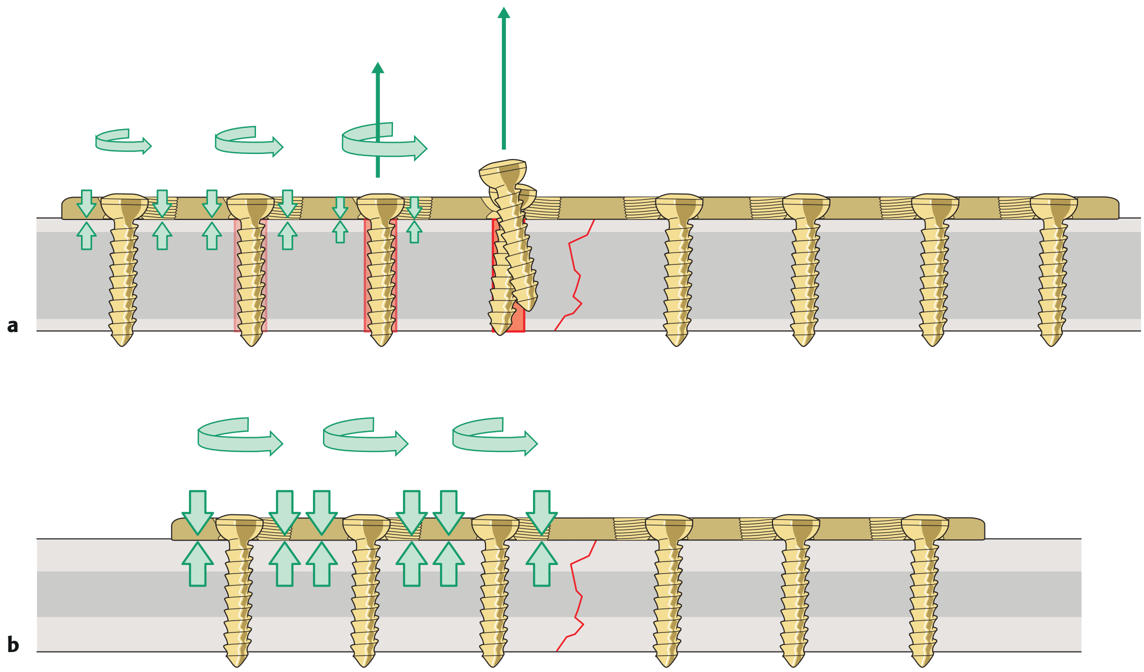


Fig 3.3.4-5a–b Conventional screw (over-) tightening in osteoporotic and normal bone.

a In osteoporotic bone with thin cortex in the diaphysis, the afforded torque on the screw during insertion (to achieve sufficient friction between plate and bone) often exceeds stability of the screw-bone interface resulting in a primary destruction of the thread in the bone. The screw has no hold at all and wiggles out of the screw hole early.

b In good bone, the conventional screws can be tightened fully creating the necessary friction between plate and bone for a stable fixation.

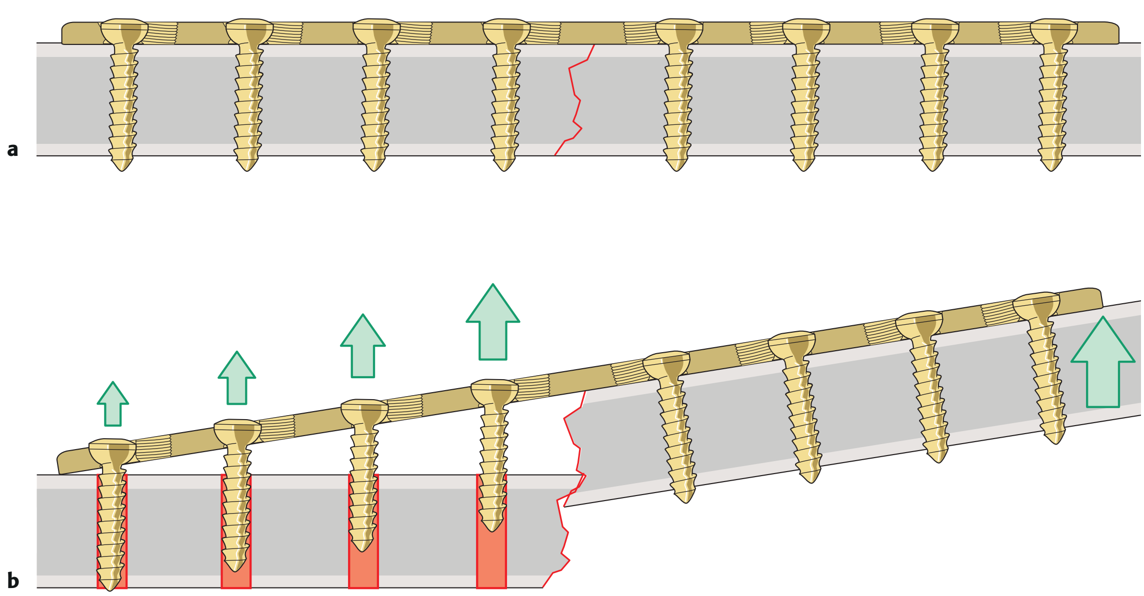


Fig 3.3.4-6a–b Sequential conventional screw loosening in osteoporotic bone. Even with correct tightening conventional screws can loosen in osteoporotic bone under cyclic loading. Bending moments on the plate are transferred to axial pull-out forces on the screws. This is maximum at the screws close to the fracture, leading to early loss of reduction.

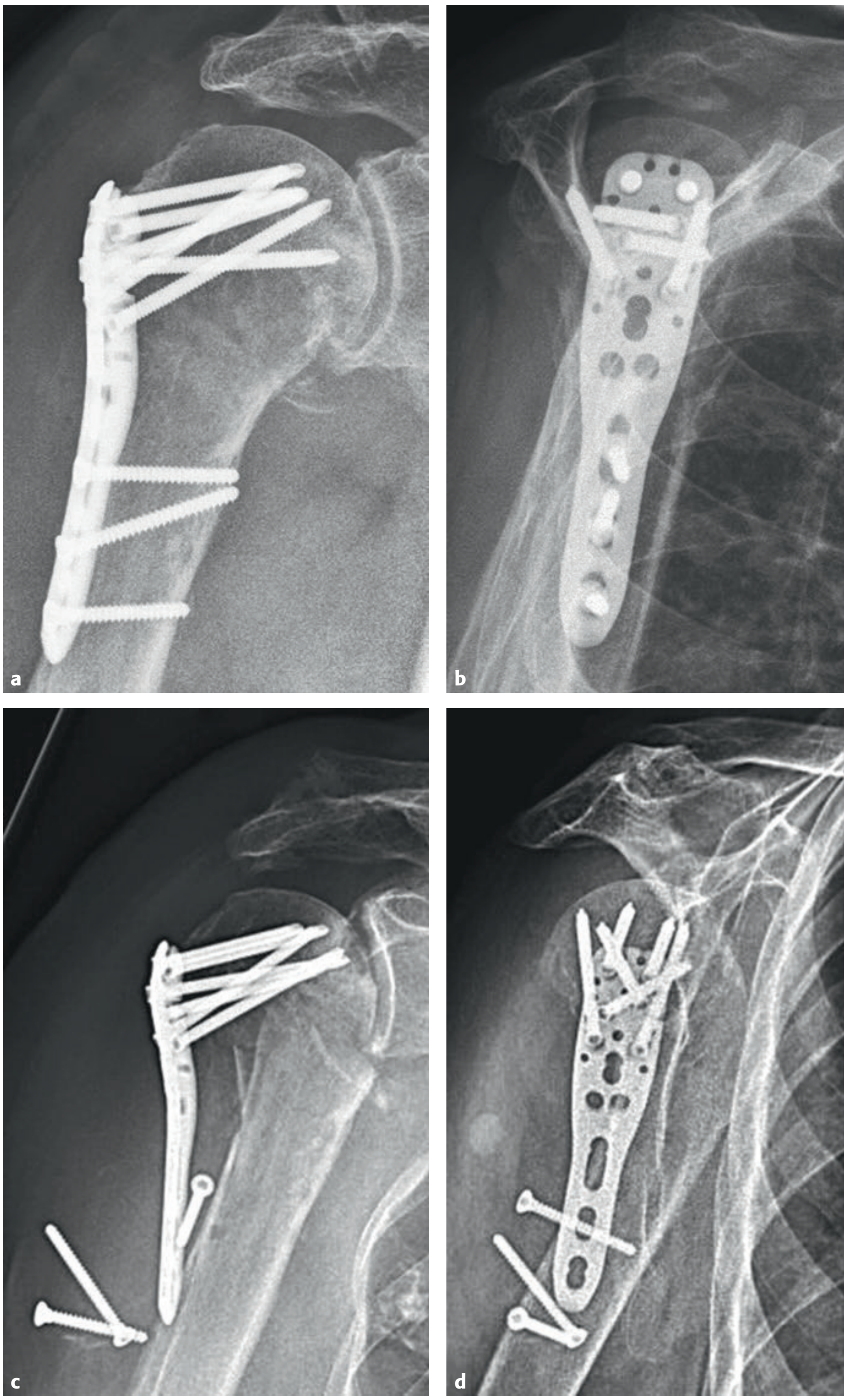
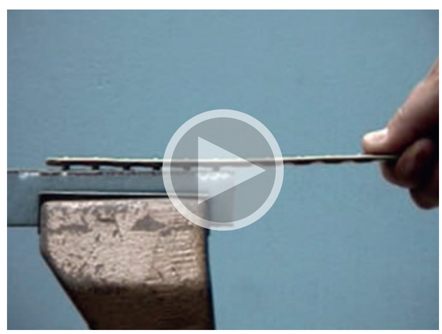


Fig 3.3.4-7a–d Early loosening of conventional screws in an osteoporotic humeral shaft. Conventional screws in osteoporotic bone can loosen early even under minimal loading. Locking head screws in this plate (or a longer plate and more conventional screws) may have prevented this implant failure.

Video 3.3.4-1

a Failure of conventional screws–sequential pullout.
b Failure of conventional screws–short plate.
c Strength of longer plate with conventional screws.

Video 3.3.4-2 Failure of conventional screws under repetitive stress.



Video 3.3.4-3 Improved strength with locking screws–no pullout.

Video 3.3.4-4 Improved strength (no pullout) with locking screws under repetitive stress.

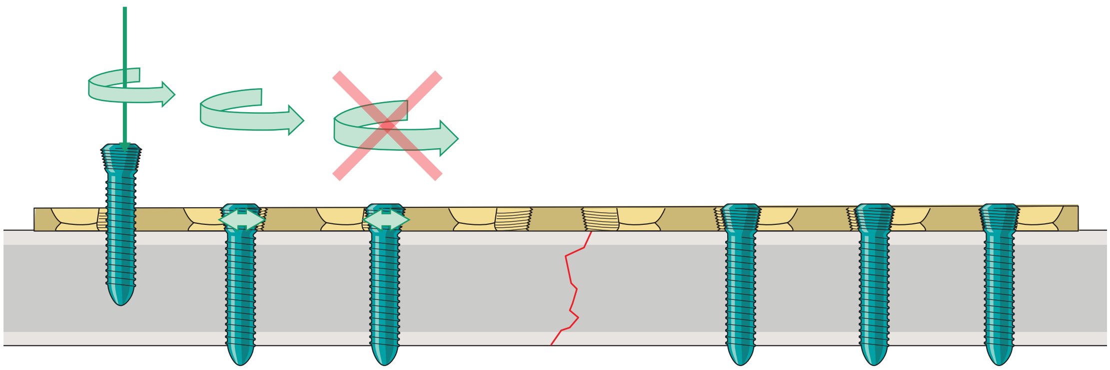


Fig 3.3.4-8 Locking screw insertion without overtightening in osteoporotic bone. Due to the locking mechanism between the screw head and plate hole, the LHS can never be overtightened in the bone. A LHS, when implanted, always advances into the bone following the created thread in the bone until the conical screw head automatically blocks further turning of the screw. Locking head screws can be overtightened in the plate hole causing deformation of the threads and jamming with difficulties for later implant removal.

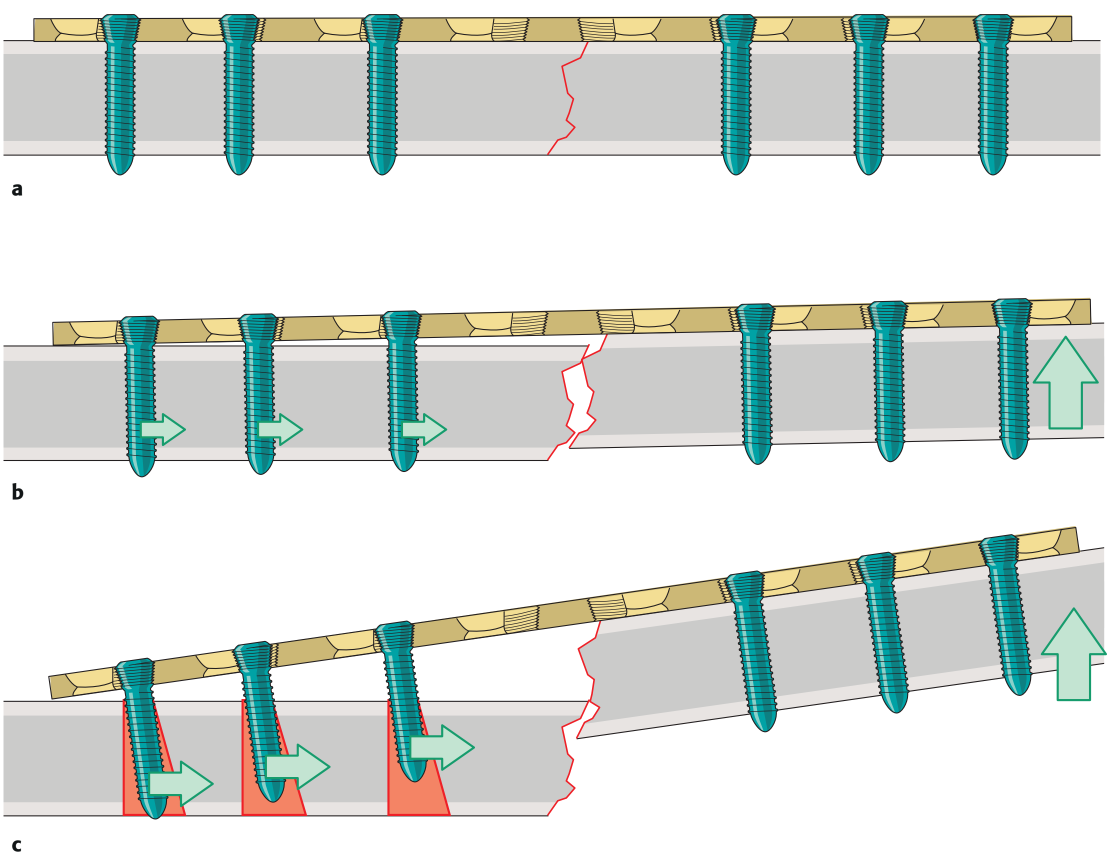


Fig 3.3.4-9a–c En bloc pull-out and cut through of locking screws in osteoporotic bone. A plate fixed to the bone with LHS provides much higher resistance against bending (and torsional) moments. The screws cannot angulate in the plate holes and therefore a large amount of bone substance has to be destroyed before bending pull-out occurs. The advantage is that loss of reduction is less likely. The disadvantage is that loss of reduction results in more bone loss (osteolysis) than seen with conventional plates.

Periprosthetic/periimplant fractures: Special monocortical screws without a tip (periprosthetic screw) (**Fig 3.3.4-10**) and other devices, such as the locking attachment plate (LAP), have been developed to allow screw insertion when the intramedullary canal is occupied by a nail or prosthesis. The VA locking screws also provide this option.

Fractures in small or soft bones require operative stabilization, such as fractures of sternum, ribs (**Fig 3.3.4-11**), scapula, face, or skull.

Revision surgery after failed plate/screw osteosynthesis: Following failed osteosynthesis with a plate and screws, the bone is often weakened by existing screw holes and osteolysis, so there is often limited space to apply new screws. Locking screws can still provide stability with monocortical insertion or in an eccentric position in the bone.

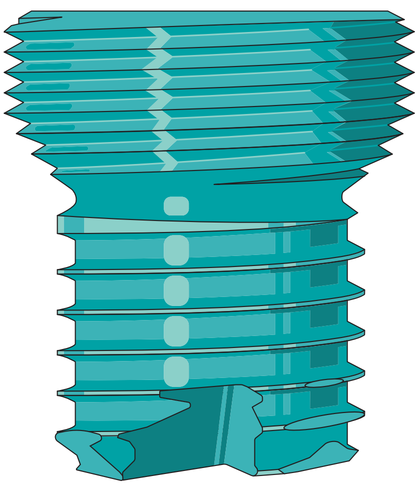


Fig 3.3.4-10 Periprosthetic locking head screw. The screw tip of this monocortical short LHS is flat for placement in the vicinity of a prosthetic stem. The threads advance as close to the stem as possible maximizing working length of the screw.

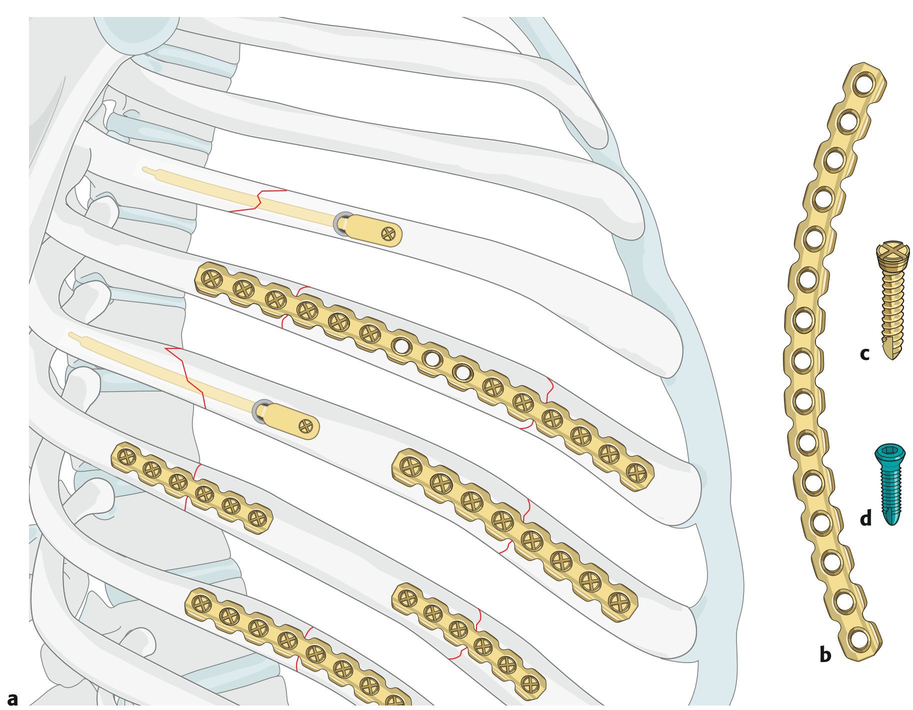


Fig 3.3.4-11a–d Locking plates for rib fractures. Fixation of rib fractures is secure with a locking plate system. The thin bone and anatomical diversity of the bone of the ribs is a perfect indication for the locking technology.

- **a** Hemithorax with multiple broken ribs and a flail segment. Fixation with precontoured locking compression plates (LCP) and intramedullary nails.
- **b** Curved precontoured LCP.
- **c** Self-tapping locking head screw.
- **d** Self-tapping conventional screw. These are not commonly used as screw loosening may result in intrathoracic migration of the loose screw.

2.3 Periarticular fractures

The second main indication for the use of locking screws is a fracture close to a joint.

The short periarticular bone segment can only be fixed with the short part of the plate. Fixation is improved by increasing the number of screws with a T-plate or L-plate but there is still a short lever arm that creates high pull-out and bending forces on the screws. Conventional screws may loosen and back-out or angulate within the plate holes, even with good bone quality. This results in early loss of reduction and instability (**Fig 3.3.4-12**). In these short bone segments, implants with angular stability are essential. This can be provided by an angled blade plate or locking screws when the plate, together with the periarticular screws, act like a "modular" angled blade plate (**Fig 3.3.4-13**). The poorest bone quality in fragility fractures is typically in the metaphysis and older adult patients with fractures in these regions benefit from the use of locking plates. For nearly all regions in the human body, anatomically preformed "periarticular" plates have been developed. The periarticular plate holes allow for the insertion of conventional or locking screws, but it is advantageous to use locking screws in the metaphysis, especially if the plate does not fit perfectly to the bone surface.

2.4 Minimally invasive plate osteosynthesis

Minimally invasive plate osteosynthesis (MIPO) is a third indication for locking plates, as these plates are easier to insert and fix compared with conventional plates and precise contouring of the plate is not required. When performing MIPO it may be difficult to position the plate in the ideal place on the bone.

Poorly contoured and/or eccentrically placed plates using conventional screws may result in early loss of stability due to poor contact between the bone and the plate or malreduction as the bone is pulled onto the poorly contoured plate when the conventional screws are tightened. This can result in axial malalignment or rotational deformity when pulling the bone to an eccentrically placed plate in the diaphysis (**Figs 3.3.4-14–15**). Using locking screws in these situations may prevent primary loss of reduction (**Fig 3.3.4-16**).

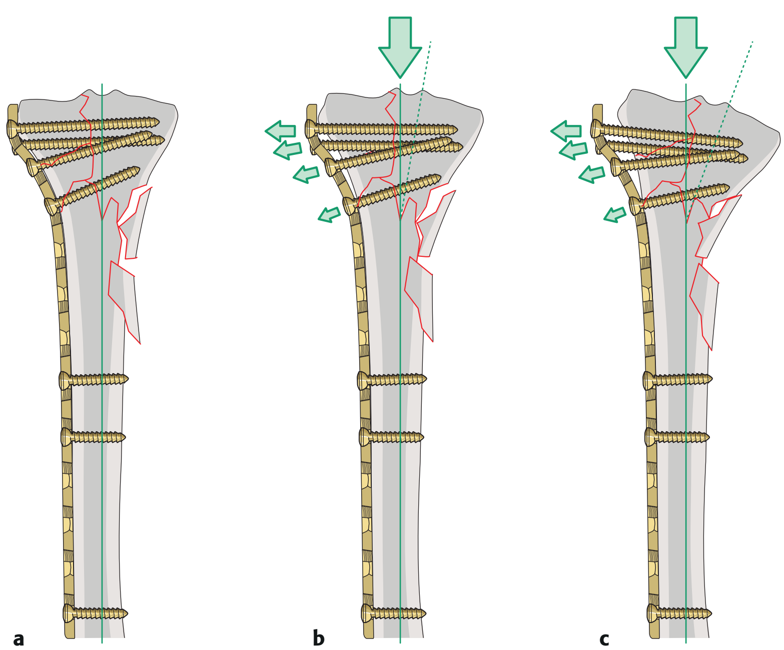


Fig 3.3.4-12a–c Secondary loss of reduction with conventional screws. In short end segments, the lever arm of the plate is short creating high pull-out forces in conventional screws. These tend to loosen early in a sequential manner, the friction between plate and bone is lost and the plate comes off the bone. This occurs because the articular block can be angulated in the coronal plane and the screws are not locked in the plate holes.

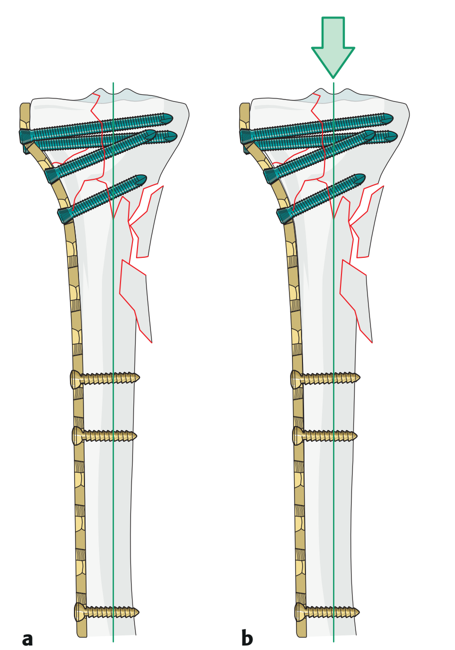


Fig 3.3.4-13a–b No secondary loss of reduction occurs with LHS which provide angular stability and therefore cannot angulate in the plate holes. The plate and all LHS combine into one unit which stays stable even in short end segments of the bone and when there is no inherent stability of the far cortex due to fragmentation.

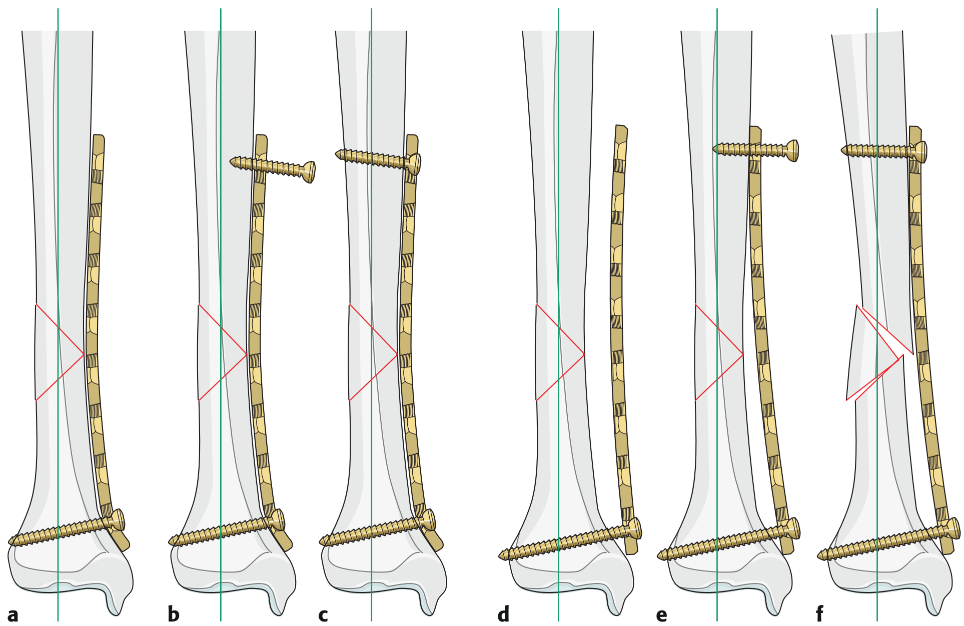


Fig 3.3.4-14a–f Primary loss of reduction with conventional screws. For the medial distal tibial plate, it is often necessary to insert a conventional screw close to the medial malleolus otherwise the plate can stand off the bone and result in skin tension when the wound is closed.

a–c If the plate is perfectly contoured (which is difficult with MIPO techniques) the insertion of conventional screws will maintain the reduction.

d–f However, if the plate is not contoured perfectly, inserting conventional screws will displace an already reduced fracture creating either an axial or torsional (or both) malalignment.

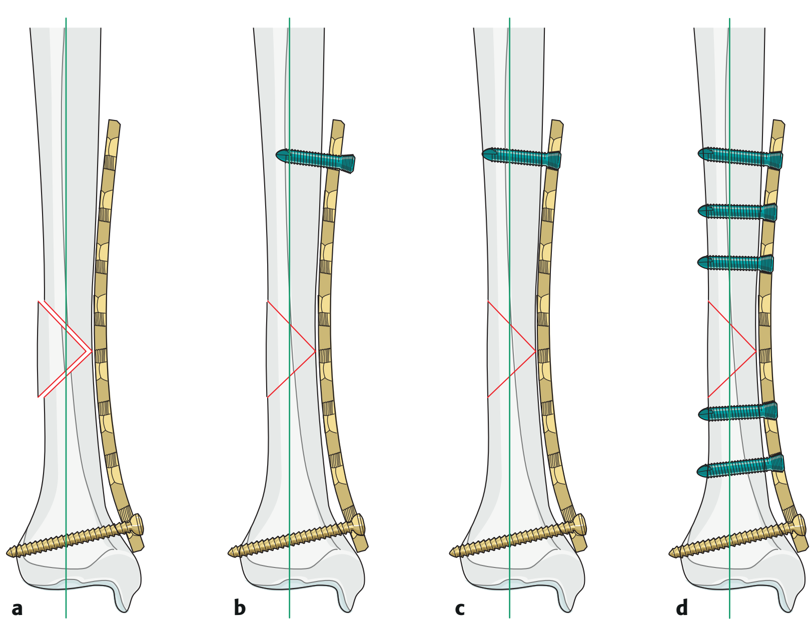


Fig 3.3.4-15a–d No primary loss of reduction with LHS. Fixing a fracture with an imperfectly contoured plate (what happens during minimal invasive plating without direct vision onto the bone surface) and LHS will not displace the already aligned fracture. When using conventional screws (for reduction and/or approximation of the plate to the bone), they must be inserted first.

3 Principles of locking screw application

3.1 General characteristics

The LHS is designed to lock tightly into the plate. This provides axial and angular stability of the screw relative to the plate. Fracture fixation with a locked plate is less dependent on the bone quality or the anatomical region for anchorage (**Fig/Animation 3.3.4-17**). Unlike the conventional screw, this screw-plate combination does not require friction between the plate and the bone to stabilize the fracture. If used as an internal fixator, ie, LHS on both sides of the fracture, force will be transferred from one bone segment to another via the plate-screw construct. In this situation, the LHS is exposed to bending load rather than tensile forces (**Fig/Animation 3.3.4-18**). Furthermore, the locking plate does not have to be contoured precisely to the shape of the bone, as tightening of the LHS does not press the implant against the bone (**Fig/Animation 3.3.4-19**). This prevents malreduction during tightening of the LHS and helps preserve periosteal vascularity underneath the implant (**Fig/Animation 3.3.4-20**).

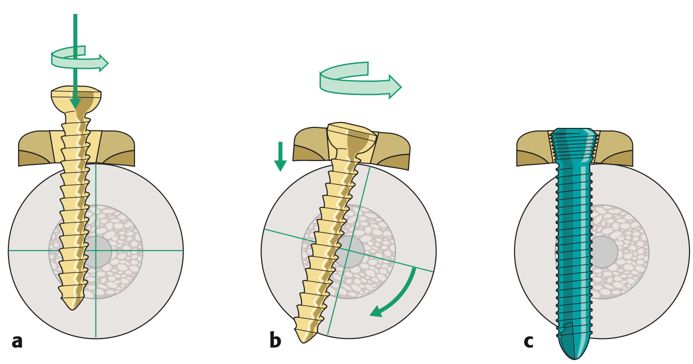
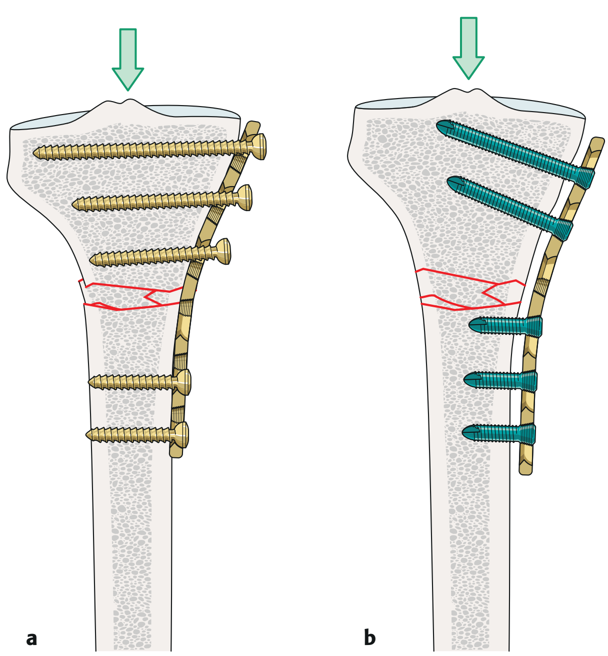
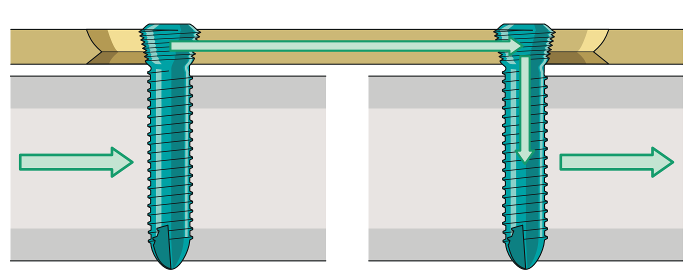


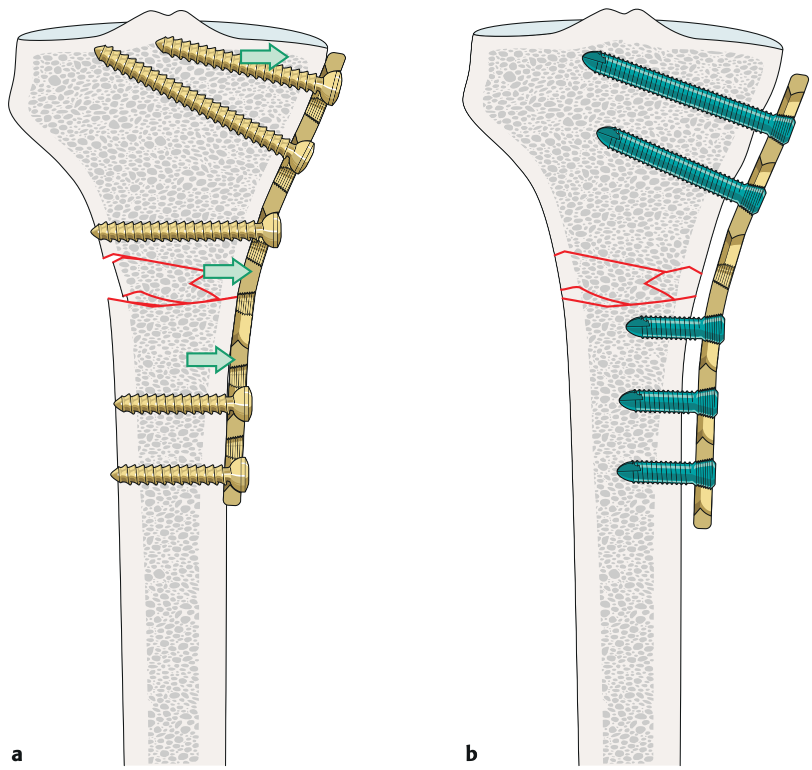
Fig 3.3.4-16a–c Primary loss of rotation with conventional screw vs LHS.
a–b A slightly eccentric plate position, which happens mainly in minimally invasive plating, will directly rotate an already correct and aligned fracture when the first conventional screw is tightened.
c This does not occur using an LHS.



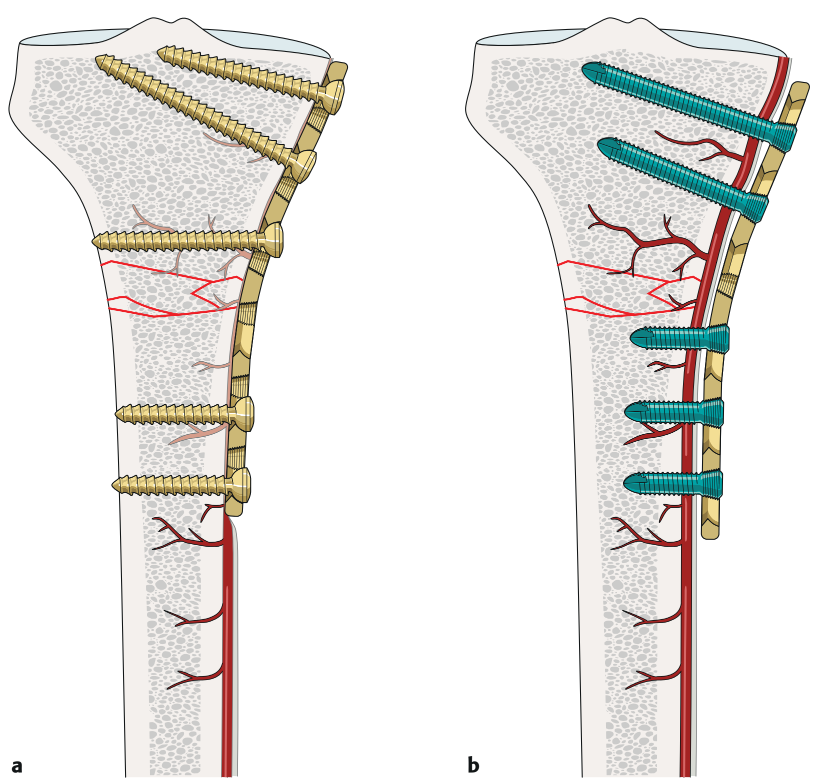
Fig/Animation 3.3.4-17a–b Loosening of conventional screws from the plate occurs sequentially, but hardly ever with locking head screws.



Fig/Animation 3.3.4-18 With locking head screws the load transmission occurs through the screws and the plate. Both are therefore exposed to bending load.



Fig/Animation 3.3.4-19a–b The LCP with LHS does not require precise contouring.



Fig/Animation 3.3.4-20a–b The LCP with LHS is not pressed against the bone. This helps preserve periosteal blood supply.

3.2 Types and functions of locking head screws

There are a number of rules for the application of the LHS. (**Table 3.3.4-2**):

- They must be used with a locking plate.
- Never use an LHS as a lag screw.
- Do not cross an unreduced fracture with an LHS, except a central articular defect in a multifragmentary articular fracture (type C3).

The correct mode of application is:

- Centered in the plate thread hole and at the correct angle using a precisely placed threaded drill sleeve (for LHS) or cylindrical drill sleeve (for VA screws only) or periarticular guide block (eg, PHILOS plate).
- Use of the correct torque-limiting attachment (TLA) for screw tightening is mandatory. This can be part of the screwdriver or power tool attachment. Overtightening can result in the screw jamming in the plate due to deformation of the thread of the screw head or plate hole. There may also be primary damage to the screwdriver recess in the screw head. All these lead to great difficulty in removing the screw and plate.

Different types of screws (**Fig 3.3.4-21**)

- Self-tapping LHS
- Self-drilling, self-tapping LHS
- Variable angle, self-tapping LHS (VA screws) (**Fig 3.3.4-4**)

Different functions of locking screws (**Fig 3.3.4-22**)

- Plate fixation screw: fixation of plate to bone. Usually applied in one or both of the two main fracture fragments.
- Position screw: keeps two (or more) well-reduced articular or metaphyseal fragments in correct relative anatomical position to each other. This function is always combined with the function of a plate fixation screw.

Function	Type of screw	Effect	Prerequirements
Lag screw • Free, plate-independent • Plate lagging screw	Cortex screw* Cortex (shaft) screw† Cancellous bone screw†	Interfragmentary compression	Gliding hole, threaded hole for a fully threaded screw or a partially threaded screw
Eccentric screw = axial compression screw	Cortex screw Cancellous bone screw	Interfragmentary compression	Dynamic compression unit and hemispheric screw head of conventional screw
Plate fixation	Cortex screw Cancellous bone screw	Friction between bone and plate	Adequate bone quality and precise fit of the plate to the bone surface
	LHS	Locking into plate, angular stability, screw loosening less common	Precise screw trajectory using threaded drill sleeve or guide, adequate tightening using torque-limiting attachment
Position screw • Free, plate-independent • Through a plate hole	Cortex screw Cancellous bone screw, fully threaded LHS (only through a plate)	Maintaining the relative position between two bones or bone fragments	Temporary fixation of the two bones/fragments during tapping and screw insertion
Reduction screw	Cortex screw Cancellous bone screw	Reduction onto the plate Reduction of a butterfly fragment at opposite side of the plate	No interfragmentary compression, only adaptation of the bone fragments
	LHS	Reduction onto the plate	Screwdriver with screw holding sleeve covering the screw head

* Using self-tapping screws as lag screws are not recommended.
† Partially threaded titanium screw.

Table 3.3.4-2 Different functions and rules for screws.
Abbreviation: LHS, locking head screw.

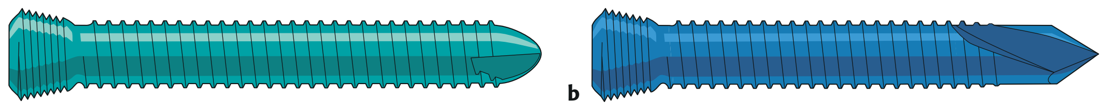


Fig 3.3.4-21a–b Different types of LHS.
a The conventional LHS is green—self-tapping but not self-drilling— commonly used in a bicortical application.
b Rarely, a blue-colored self-drilling/self-tapping screw can be used in a monocortical mode (traditionally used for the LISS when inserted through the drill sleeves of the aiming jig). This screw is not advised for bicortical application because the tip must penetrate further through the far cortex and may cause soft-tissue damage (**Fig 3.3.4-18**).

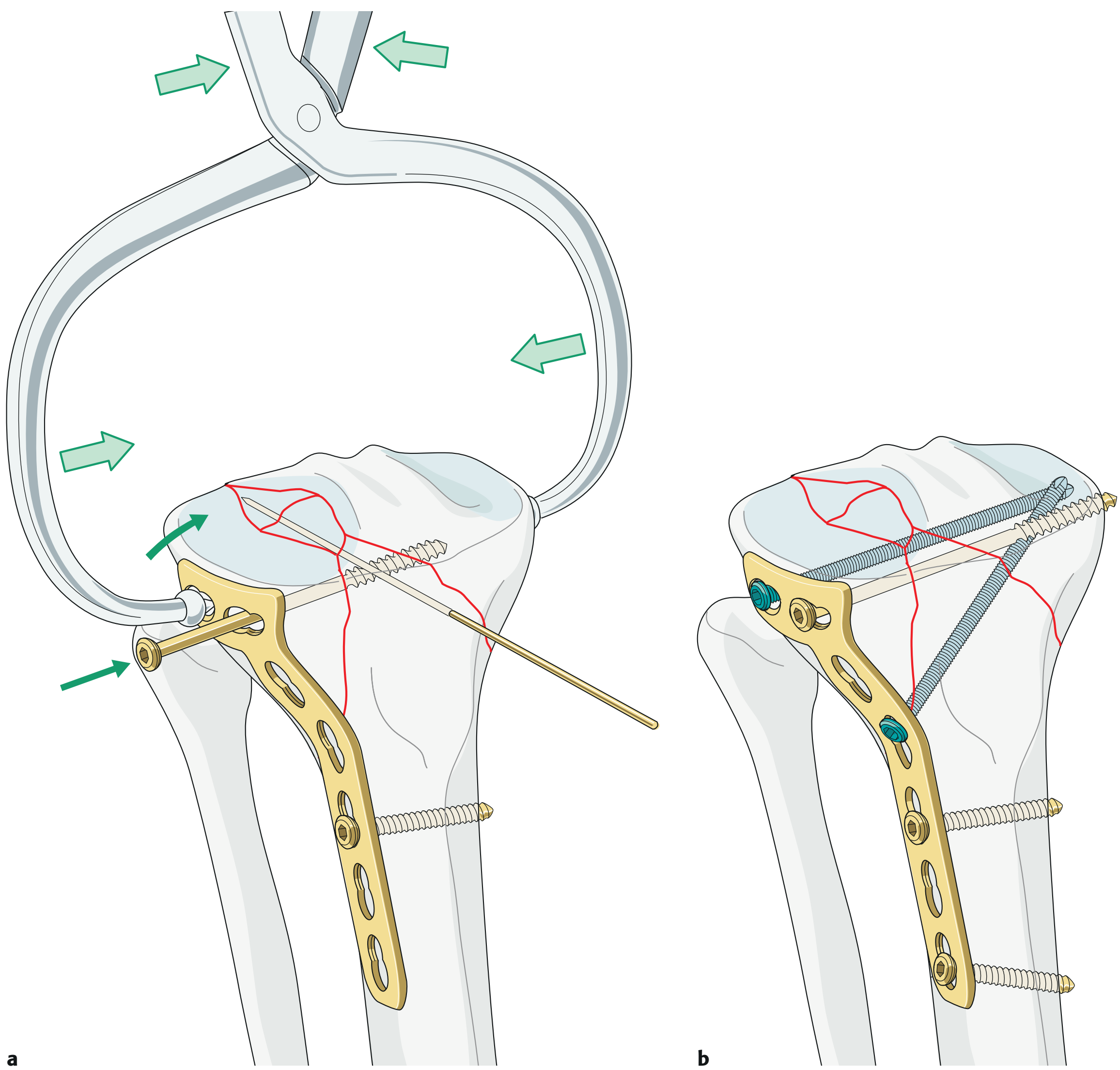


Fig 3.3.4-22a–b Fixation of a proximal tibial fracture showing the different functions of screws.
a The fracture is reduced and held with a combination of clamps and K-wires. Standard screws are used to fix the plate and provide compression across the articular fracture.
b Locking head screws are then used to complete the fixation and function as a position screw across the multifragmentary articular fracture and as plate screws.

3.3 Monocortical or bicortical locking head screws

The bicortical LHS is recommended in most situations in the diaphysis, as the screw has a much longer working length. This is especially advised in osteoporotic bone (**Fig 3.3.4-23**).

Only self-tapping LHS are used for bicortical application. Self-drilling/self-tapping screws in bicortical application are not recommended as they can irritate and damage soft-tissue structures with their sharp screw tip (**Fig 3.3.4-24**).

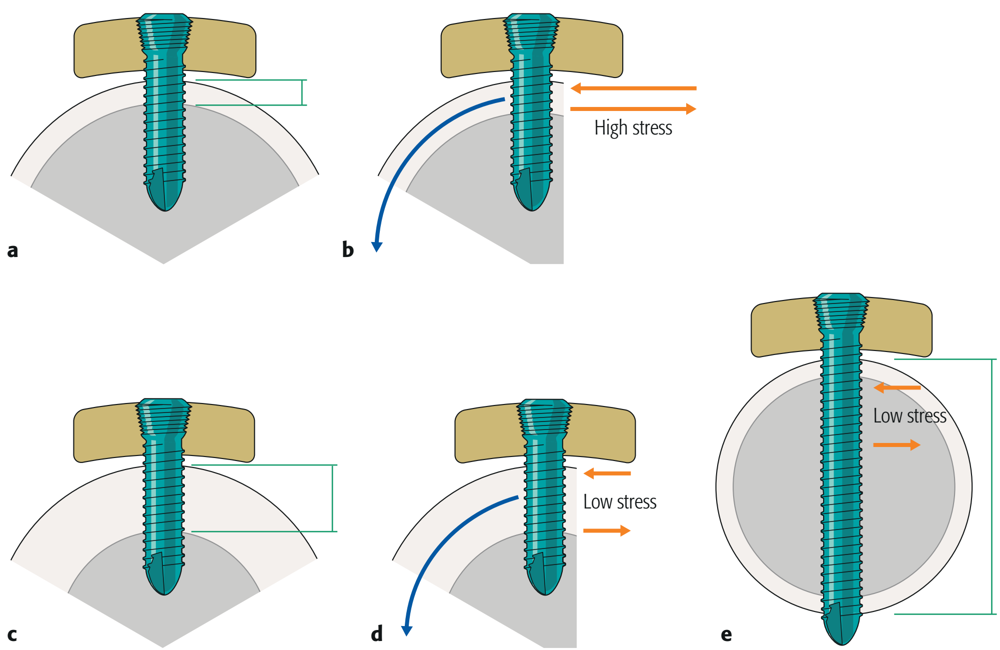


Fig 3.3.4-23a–e Working length of locking head screws. Length of screw thread in contact with bone influences stress at screw-bone interface. A short working length exists when there is thin bone cortex or monocortical screw insertion. This results in high stress at the interface (**a–b**). A long working length exists when there is thick bone cortex or bicortical screw insertion. This results in low stress at the interface (**c–e**).

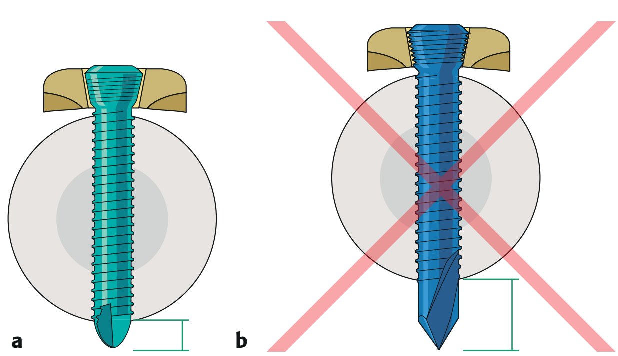


Fig 3.3.4-24a–b Self-drilling and self-tapping bicortical locking head screws (LHS). Bicortical application is reserved for the self-tapping LHS (**a**) and should be avoided using a self-drilling self-tapping LHS (**b**).

"Subbicortical" periarticular LHSs are used close to joints and traverse the full distance of the cancellous bone but do not penetrate the opposite cortex (**Fig 3.3.4-25**). This guarantees the longest working length but prevents:

- Soft-tissue irritation on the opposite side of the bone (eg, extensor tendons at the wrist when using a palmar distal radial plate, or femoral origin of MCL when using lateral distal femoral plate) (**Fig 3.3.4-26**)
- Intraarticular screw tip penetration on the opposite side of the bone (eg, proximal humerus or distal humeral lateral condyle)
- Screw tip penetration into the tibiofibular syndesmosis in distal tibia or fibular plating

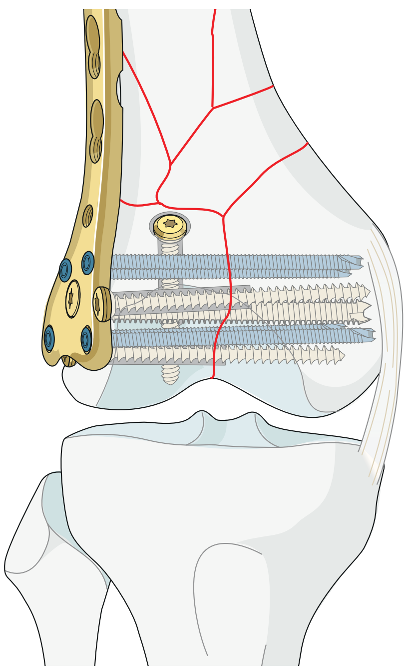


Fig 3.3.4-25 Correct length of locking head screws (LHS) in the distal femoral metaphysis. Especially in poor bone quality, the LHS in the metaphysis should have the longest possible working length. However, the screw tips should not penetrate the opposite cortex irritating soft-tissue structures such as ligaments or tendons. They are neither monocortical nor bicortical, what could be named as "subbicortical" (= nearly bicortical).

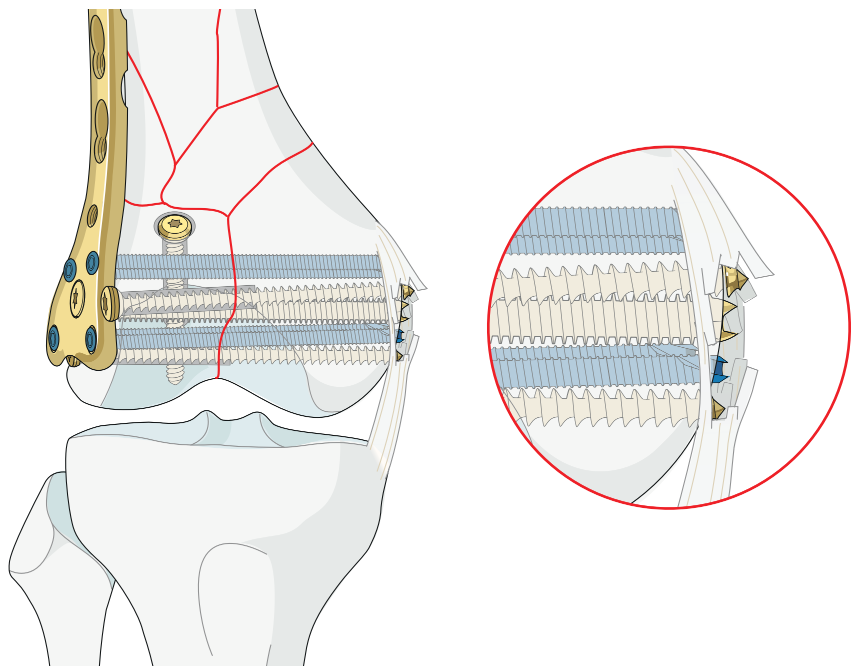


Fig 3.3.4-26 Locking head screws (LHS) that are too long in the distal femoral metaphysis. Bicortical LHS in certain locations, such as distal femur (or distal radius) may irritate important soft-tissue structures and therefore should be avoided in these regions.

Screws that are too short in poor bone result in early loss of reduction and deformity (**Fig 3.3.4-27**).

Monocortical screws are occasionally used in the following circumstances:

- Periprosthetic fracture: The periprosthetic screw (flat screw tip) (**Fig 3.3.4-10**) increases working length of the screw compared with the normal LHS.
- Temporary reduction plates: Small plates (2.4, 2.7, or 3.5) may be used to hold a reduction during definitive fixation with a nail or larger plate. Monocortical screws are helpful and do not block reamers, nails, or screws in the medullary canal.
- Supplementary fixation in good diaphyseal bone (fixation that relies on monocortical screws alone is not advised).
- Long spiral fracture: may enhance fixation to allow for the use of a shorter plate (**Fig 3.3.4-28**).

3.4 Number of screws

Rules for the use of bicortical LHS:

- Two bicortical screws in each main fragment can be used with a longer plate in good bone quality and with an expected short healing time (good vascularity, good reduction, and a low-energy injury). The position of the screws must be perfectly centered to the bone (not tangential). There is little room for error and less experienced surgeons should always consider using more than two screws.
- Three bicortical screws in each main fragment should normally be used.
- Four (or more) bicortical screws are advised in osteoporotic bone, especially in bones with torsional loading (eg, humerus).
- Using a locked screw in the last screw hole at the end of the plate can produce a stress riser and may be associated with an increased risk of periimplant fracture, particularly in osteoporotic bone. Surgeons should consider using a bicortical conventional screw in this position. If it is inserted after LHS, care should be taken not to overtighten the screw [8].

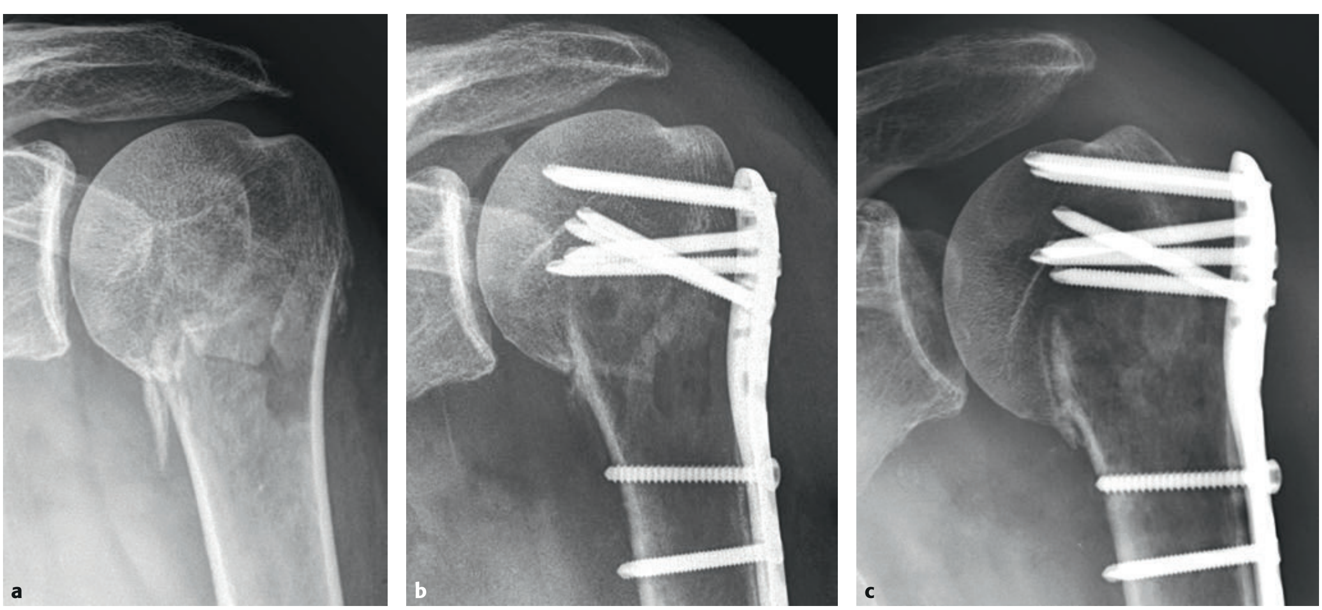


Fig 3.3.4-27a–c Short locking head screws in a humeral head with early varus malangulation.
a–b In an osteopenic humerus, the bone which has adequate quality to provide a stable screw-bone interface is sited close to the cartilage near the subchondral region. The LHSs inserted in the humeral head should be long enough to anchor the screw tips in this more solid bone.
c If chosen too short, as in this case after 6 weeks, early instability with varus collapse can occur.

4 Locking compression plate

4.1 General characteristics

The unique feature of the LCP is the combi-hole, which can accommodate either a conventional screw or LHS. The first part of the combi-hole has the design of the conventional DCP/LC-DCP compression hole (dynamic compression unit) which accepts a conventional screw to produce axial compression or the placement of an angled lag screw through the plate. The second part is conical and threaded to accept the LHS and its position is close to the plate center in straight plates or close to the location of fracture in periarticular plates (**Fig 3.3.4-8**).

All conventional plates from the different systems (4.5, 3.5, 2.7, and smaller) (LC-DCP, L-plates, and T-plates, as well as reconstruction plates) have been made with the combi-hole, but without any change in the overall plate dimensions. The periarticular portion of most anatomically preshaped LCP's consists of round, conical, threaded plate holes for the insertion of LHSs but they can also accept conventional screws if desired.

In some new plate systems, VA technology is incorporated in the plate holes to allow insertion of variable angle locking screws at 15° to the perpendicular screw trajectory.

4.2 "Hybrid" application of locking compression plate

When both locking and nonlocking screw types are used in one plate, it can be called "hybrid" application [9]. In the last 10 years, this method of application has been increasingly practiced. Several biomechanical and clinical studies on large bones have shown that the combination of locking and conventional screws is effective. The capacity to resist torsional forces is significantly higher when the locking plate is applied with the hybrid technique to the lateral distal femur [10]. It is first fixed distally to the condyles with a conventional screw(s), then augmented with locking screws. This may be because the broad, anatomically preshaped part of the plate gives additional torsional stability when pressed against the bone. If there is good bone stock, conventional screws can be used to fix the plate to the diaphysis.

Similar results were reported on patients undergoing a medial high-tibial osteotomy with lateral hybrid plating [11]. However, incorrect application of hybrid plating systems can run the risk of failing to achieve either absolute or relative stability. This may create an environment with high strain. The result is implant failure and delayed or nonunion [12].

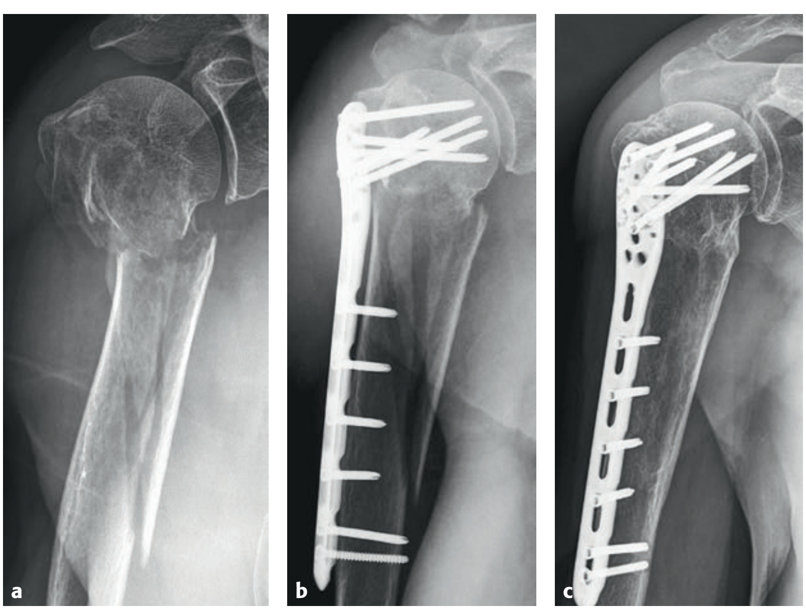


Fig 3.3.4-28a–c Monocortical locking head screw (LHS) in a long spiral fracture (**a**). Using monocortical screws to supplement bicortical LHS, the afforded total length as well as the working length of the plate can be reduced to the desired length (**b**). Four-year follow-up x-ray (**c**).

Careful preoperative planning with a clear aim to produce absolute or relative stability is essential when using an LCP as a hybrid plating system. Optimal interfragmentary or plate-to-bone compression must be achieved before the application of the locked screws (lag first, lock second).

4.3 Biomechanics of the locking compression plate

The LCP can be used to provide the six standard functions of a plate:

- Compression
- Protection
- Buttress
- Tension band
- Bridging
- Reduction

All these functions can be provided by using conventional screws or with hybrid fixation using a combination of locking and conventional screws. With locking screws alone, an LCP can function as a protection, buttress, tension band, or bridge plate but cannot be used as a compression plate or reduction tool.

In any individual case, one of the different plate functions should be ideal and the surgeon must plan according to the fracture location, fracture pattern, bone quality, and the soft-tissue situation. The correct execution of the preoperative plan depends upon many factors, including the method and quality of reduction, length of plate, the number and type of screws, and their sequence of insertion (**Table 3.3.4-3**). To produce the different plate functions, conventional screws only, locking screws only, or both screw types ("hybrid" application) may be used.

	Simple fracture (A-type and B2-type)		**Multifragmentary fracture (B3-type and C-type)**
Biomechanical principle	**Interfragmentary compression**	**Splinting ± reduction lag screw**	**Splinting**
Reduction technique	Mainly direct	Indirect or percutaneous direct*	Preferably indirect
Insertion	At least partly open	Open, less invasive, MIPO	Closed, minimally invasive
Contouring of the plate	Has to be precise to bone surface	Accurate contouring not needed with LHS	Accurate contouring not needed with LHS
Plate span ratio†	8–10 (in transverse or short oblique fracture), 2–3 (in long spiral fracture)		2–3 (in long fracture zone), 4–8 (in short fracture)
Screw type	For compression: cortex screws in eccentric position or lag screw For plate fixation: cortex screw in neutral position or LHS‡	Cortex screws or LHS‡	Cortex screws or LHS‡
Monocortical/bicortical screws	Cortex screws: bicortical LHS: bicortical. Monocortical screws around implants for periprosthetic fractures		
LHS in the diaphysis	Bicortical, self-tapping screws Monocortical self-drilling "periprosthetic" screws for periprosthetic fractures Monocortical self-drilling/self-tapping screws are optional in good bone in diaphysis (eg, LISS with aiming arm)		
LHS in the metaphysis	Self-tapping screws (as long as possible, but not perforating opposite bone surface)		
Plate screw density	≤ 0.6–0.8	≤ 0.4–0.5	≤ 0.4–0.5
Screws per main fragment (n)	≥ 3 (2 exceptionally)	≥ 3 (2 exceptionally)	≥ 3 (2 exceptionally)
Cortices per main fragment (n)	≥ 5–6	≥ 4	≥ 4
Screw position	Close to the fracture, aiming for absolute stability	Middle segment (≥ 2 plate holes) without screws, no lag screws (splinting method)	Fracture zone without screws, but screws close to the fracture
Empty plate holes over the fracture (= plate working length)	0–2	≥ 2	≥ 2

* When splinting simple fractures, reduction must be accurate: gap free or at least gap < 1–2 mm (= near anatomical).
† Plate span ratio = plate length/fracture length.
‡ In epiphysis/metaphysis and/or in poor bone and/or in MIPO technique.

Table 3.3.4-3 Guidelines for plate fixation in simple and multifragmentary diaphyseal and metaphyseal fractures.
Abbreviations: LHS, locking head screw; LISS, less invasive stabilization system; MIPO, minimally invasive plate osteosynthesis.

The method of fracture treatment and type of stability produced leads to different types of fracture healing and the LCP allows the surgeon to select the correct biomechanical environment for the fracture, producing either absolute or relative stability. With proper use, the LCP can significantly contribute to the improvement of the clinical outcome following operative treatment of fractures. The first published results on the use of LCP have been promising but have identified difficulties and complications [5], many of which were due to application errors [13] despite the publication of guidelines for the correct use of the LCP [6]. Clinical experience with the use of LCPs has grown [14–17].

4.4 Absolute stability with the locking compression plate

Anatomical reduction and interfragmentary compression of simple fracture patterns (type A or type B2) can be achieved with the LCP. The reduction should result in no fracture gap and the plate is placed on the tension side of the bone. This plating technique is currently reserved for the articular segments of fractures or simple diaphyseal fractures where anatomical healing is needed. Plate fixation of both bone forearm fractures is a common example. With good bone quality and direct, anatomical reduction, there is no need to use locking screws [18] and the fracture can be fixed with conventional screws following AO principles. However, experienced surgeons know that absolute stability may be lost in the early stage of bone healing, leading to some instability with callus formation (irritation callus). In a recent retrospective study [19] of simple (type A and type B2) humeral shaft fractures treated with compression plating techniques, more than 40% of the healed cases showed callus formation with secondary bone healing. This demonstrated that planned absolute stability was only achieved in 60% of cases and that absolute stability is not mandatory for good healing of simple diaphyseal humeral fractures. The most important and statistically significant factor for healing was the size of fracture gap on radiographs [19] ($P = .001$) and this emphasizes that anatomical reduction and compression is essential if the surgeon is to achieve absolute stability.

The LCP using both conventional and locked screws can be used in a number of situations:

Simple metaphyseal fractures in osteoporotic bone: The fracture is reduced and held by one or more lag screws, carefully tightened due to poor bone. The LCP functions as a protection plate and is fixed with one or two conventional screw(s) to each main fracture fragment to approximate the plate to the bone. Further plate fixation is carried out adding bicortical LHSs following the guidelines in (**Table 3.3.4-3**). Alternatively, the protection plate is approximated to the bone by manual push (instead of conventional screws first) and then fixed entirely with LHS on both sides (**Fig 3.3.4-29**).

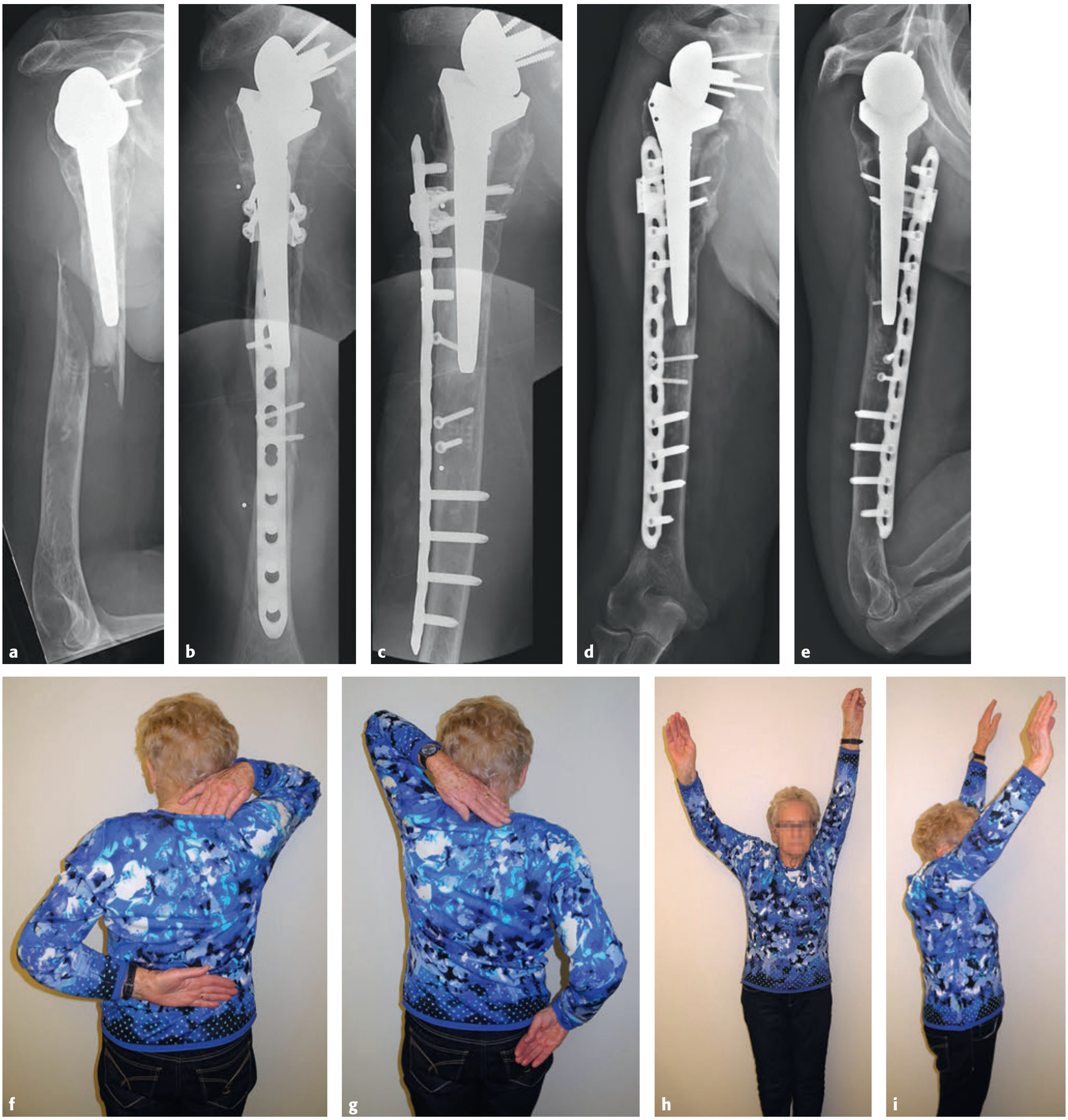


Fig 3.3.4-29a–i Periprosthetic 12A1 fracture in osteoporotic bone treated with a compression technique using a locking compression plate (LCP) with locking head screw (LHS) for entire plate fixation.

a An 85-year-old woman with a simple periprosthetic fracture below a shoulder prosthesis, and severe osteoporosis with thin cortical bone.

b–c The fracture is approached with an open incision, anatomically reduced and maintained by three 3.5 mm lag screws carefully tightened. These screws reduce the fracture until plate application, but can not provide strong interfragmentary compression because of the poor bone quality. The forces are neutralized with a long narrow LCP 4.5 which is fixed to the bone by LHSs only. In the proximal piece, short monocortical periprosthetic screws are used, and the fixation is enhanced by a locking attachment plate. To reduce the risk of periimplant fracture distally, one monocortical screw is used at the plate end.

d–i One year follow-up images.

Periarticular fractures (with or without articular involvement): The anatomically precontoured plate is fixed to the articular part with LHSs providing angular stability. Interfragmentary compression is achieved using a lag screw or with the plate using a conventional screw in a dynamic screw hole or the articulated tensioning device. The definitive fixation to the diaphyseal main fragment is entirely done with conventional screws in good bone (**Fig 3.3.4-30**) or with one or two conventional screws followed by 2–3 bicortical LHS in poor bone (**Fig 3.3.4-31**). If there is an articular fracture, this is reduced first and compressed by independent lag screws or screws through the plate. Occasionally, the articular fracture is compressed by reduction forceps applied onto the plate, using it as a "washer." Some plating systems are instrumented with special compression devices that attach onto the plate itself. Following reduction and compression, LHSs are inserted and function simultaneously as position screws to hold the articular fracture reduction and plate fixation screws (**Fig 3.3.4-32**).

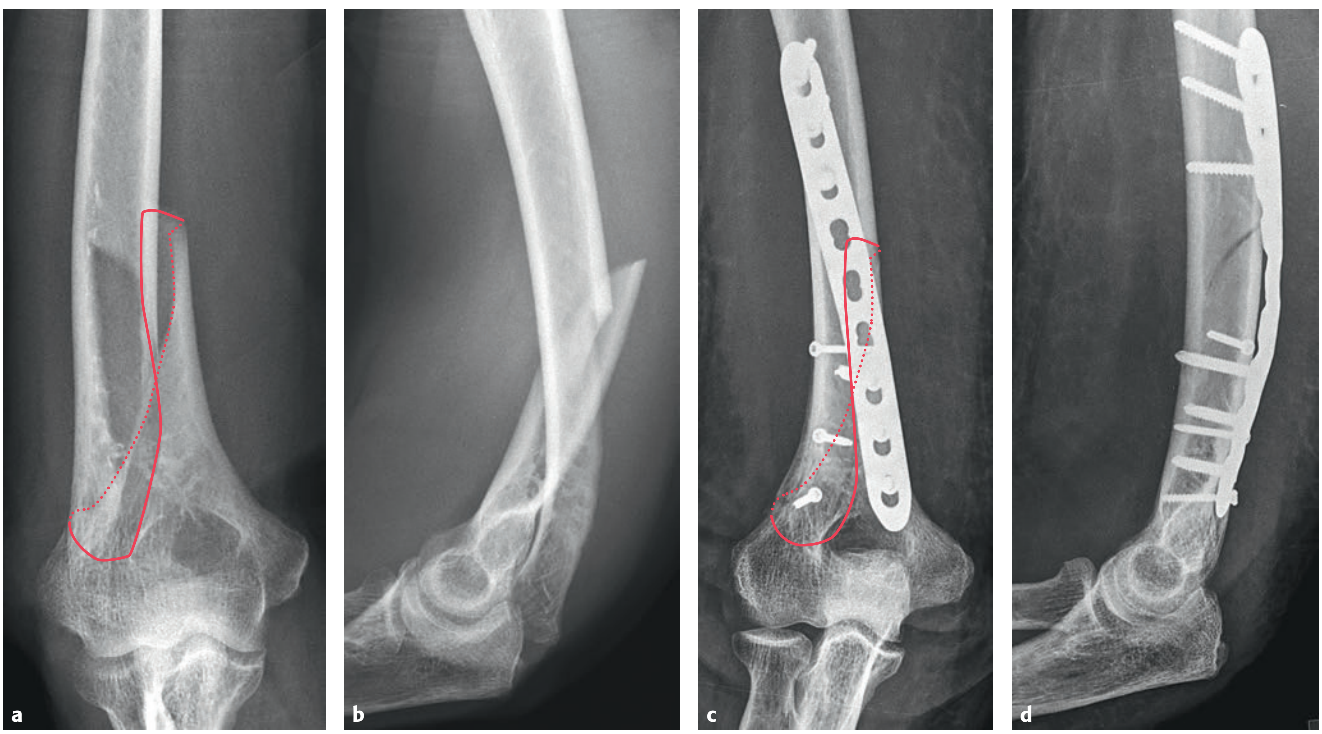


Fig 3.3.4-30a–d A 12A1 distal humeral fracture treated with a compression technique with a locking compression plate (LCP) and locking head screws (LHS) in the metaphysis and conventional screws in the diaphysis.

a–b A 75-year-old woman, with simple torsional fracture at the distal metadiaphysis of the humerus with moderate bone quality.

c–d Open anatomical reduction and fixation by three 3.5 mm lag screws is followed by fixation distal of the precontoured and twisted narrow LCP 4.5 with three bicortical LHS. The main fracture is additionally compressed by insertion of a conventional screw at the proximal plate end in eccentric position, followed by two other conventional screws to finish the fixation.

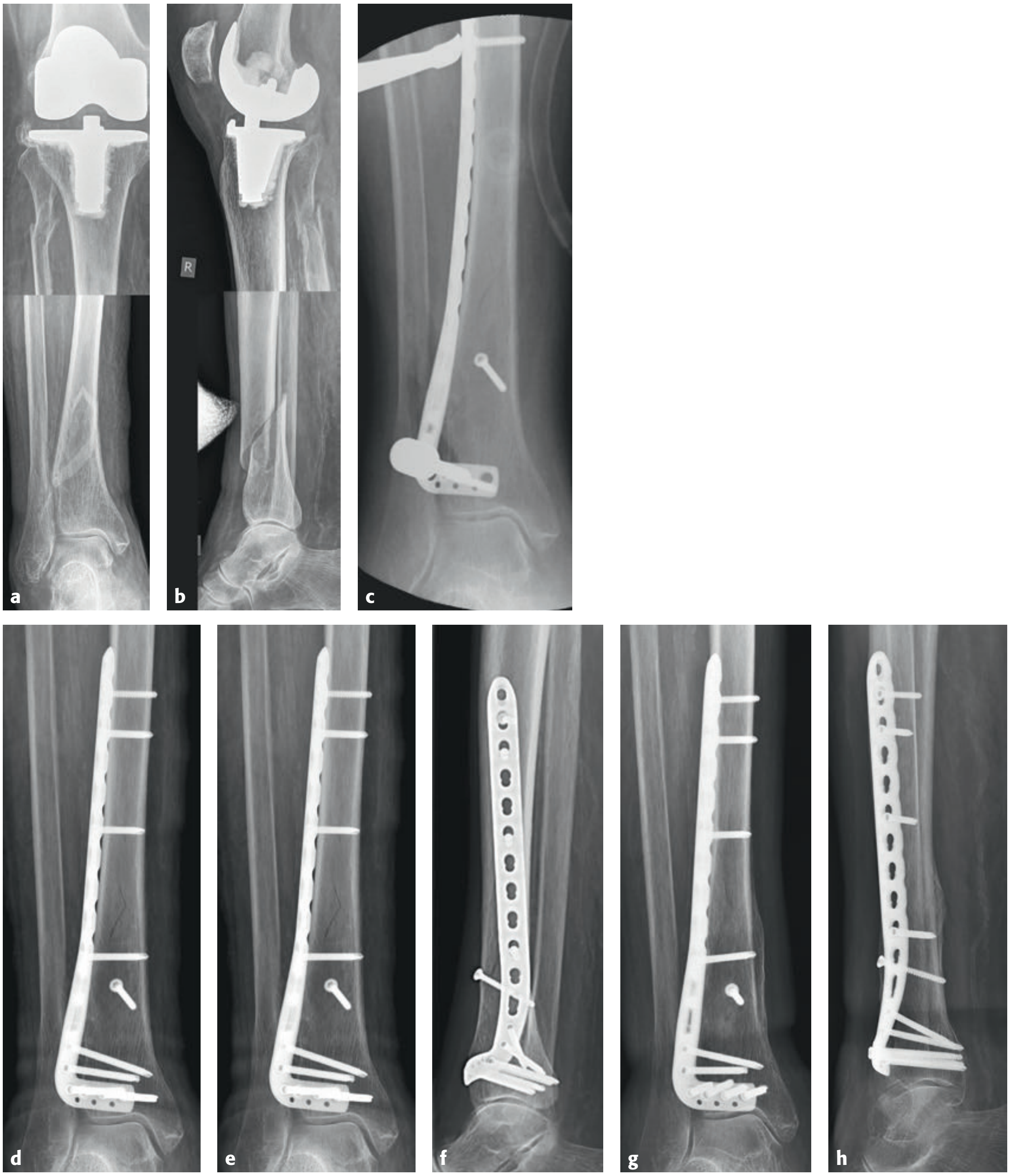


Fig 3.3.4-31a–h A 42A1 distal tibial fracture in osteoporotic bone treated using a compression technique with locking compression plate (LCP) in "hybrid" application.

a–b A 76-year-old woman, suffers a low-energy trauma with simple torsional fracture at the distal tibial metadiaphysis. Total knee arthroplasty in place makes intramedullary nailing impossible.

c A distal anterolateral approach is performed; the fracture in the distal part visualized and anatomically reduced with reduction forceps. A reduction screw (lag screw principle, carefully tightened in this poor bone) keeps this position until the plate is inserted through the distal approach submuscularly at the proximal end. Preliminary fixation distally is achieved, and then a conventional cortical screw is inserted percutaneously in the most proximal plate hole to bring the well-centered plate close to the bone.

d–f Final fixation is carried out with locking head screws only due to poor bone quality. Where possible, periprosthetic fractures should have the whole bone plated, as is the case here. The fracture fixation worked but guidelines should be followed.

g–h After 1 year, healing occurs indirectly with callus formation despite compression technique being applied. This construct with one (plate) independent lag screw "protected" by this rather flexible and long LCP with, few but well-separated screws in the diaphysis provides only for a short time (if at all) absolute stability. With partial loading, even when protected with a cast or walking splint, this absolute stability is lost. Relative stabilty results with micromotion at the fracture side and consequent callus formation mainly at the opposite side of the plate (posteromedial).

Fig 3.3.4-32a–j A 13C3 fracture treated with a compression technique with locking compression plate (LCP).

a–b A 54-year-old man, fell from a motorbike, sustained a dorsal grade 2 open distal multifragmented intraarticular humeral fracture.

c–d Dorsal approach was used with olecranon osteotomy. The anatomically reduced and compressed articular part is fixed with locking head screws (LHS) functioning on one hand as position screws for the articular fragments and on the other as fixation screws for the plate, providing angular stability to overcome secondary flexion collapse. The dorsal and ulnar aspects of the metaphysis (simple fracture lines) are compressed over the plate using a conventional cortical screw in both the most proximal plate holes. Definitive diaphyseal plate fixation is carried out with conventional screws on the ulnar side, where the plate fits perfectly to the bone, and two LHS on the radial side, where the plate had a slight distance to the bone surface.

e–f After 6 months, healing occurred directly (articular part) and indirectly with callus at the anterior metaphysis.

g–j One year follow-up images.

Minimal invasive plating (MIPO) of a simple type A fracture: Metaphyseal and diaphyseal fractures with simple fracture patterns can be treated successfully using MIPO (**Fig 3.3.4-33**). The length of the incisions in the soft tissues can be minimized to preserve the blood supply of the skin and underlying tissues as much as possible. It is crucial to achieve a perfect, anatomical reduction of the simple fracture. Several reduction techniques can help achieve this goal. Pointed reduction forceps correctly placed through small incisions, in combination with percutaneous lag screws, help obtain a gap-free reduction prior to the insertion and fixation of the plate. Conventional screws, one each at both plate ends, are first used to approximate the plate to the bone. Locking head screws are added percutaneously for definitive fixation. An alternative technique is to reduce the fracture but not use lag screws. A longer plate and fewer screws are used to provide more flexible fixation, producing relative stability and secondary bone healing with callus formation.

Experience with MIPO has shown that the quality of reduction is the most important factor for successful and timely healing.

Combining conventional screws and LHSs in one (and the same) fracture fragment ("hybrid" application) must follow one simple rule: do not tighten a conventional screw if an LHS is already inserted and locked.

This means that either the conventional screws are inserted first, followed by the LHSs, or an already inserted and locked LHS must be disengaged (turned back until the screw head is not engaged in the threaded plate hole) before a conventional screw is added in the same fragment. This technique is used in MIPO to approximate an inserted and fixed plate (with LHSs) that stands off the bone putting tension on the adjacent soft tissues or wound.

4.5 Relative stability with the locking compression plate

Multifragmentary metaphyseal and diaphyseal fractures are best treated using relative stability because:

- Anatomical reduction and interfragmentary compression cannot be achieved.
- Direct reduction damages the local vascularity of bone and soft tissue.
- Relative stability allows functional rehabilitation and results in healing of multifragmentary fractures by callus formation.

Fig 3.3.4-33a–o A 42B2 distal fracture treated with a compression technique with locking compression plate (LCP) in "hybrid" application.
a A 55-year-old man suffered a ski accident with a closed injury. A distal metadiaphyseal fracture of the tibia was present close to the joint.
b–c A minimally invasive plate osteosynthesis technique kept the iatrogenic damage to the soft tissues minimal.

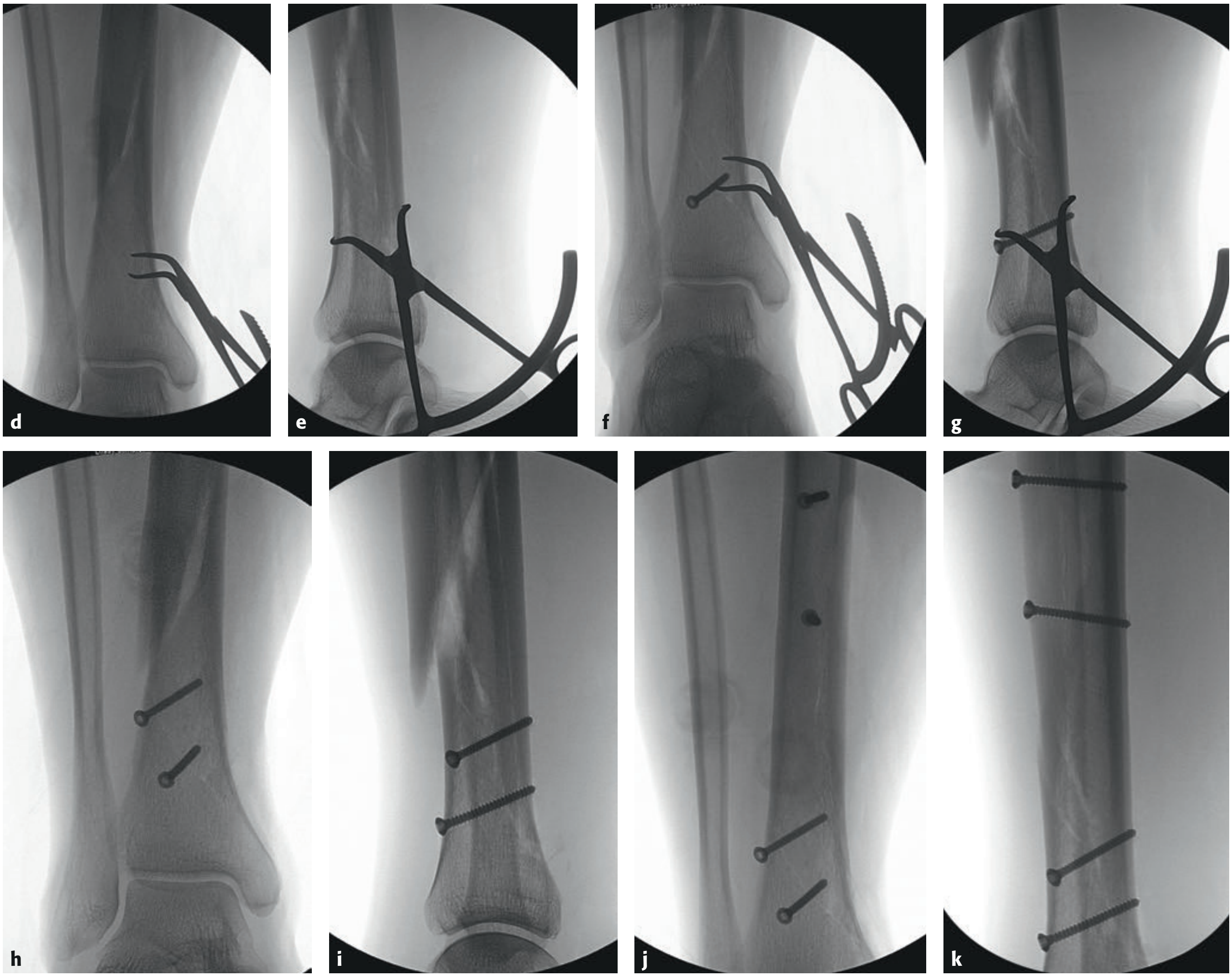


Fig 3.3.4-33a–o (**cont**) A 42B2 distal fracture treated with a compression technique with locking compression plate (LCP) in "hybrid" application.
d–g Most important was the reduction of the two simple fracture planes between the two main and the long butterfly fragments. One option is to use a pointed reduction forceps inserted by two stab incisions in ideal position.
h–k The gap-free (ideally: anatomical) reduction can be retained by percutaneously applied "retention" screws, at least one per fracture plane. These screws allow for removing the reduction forceps which will be a hindrance for plate insertion.

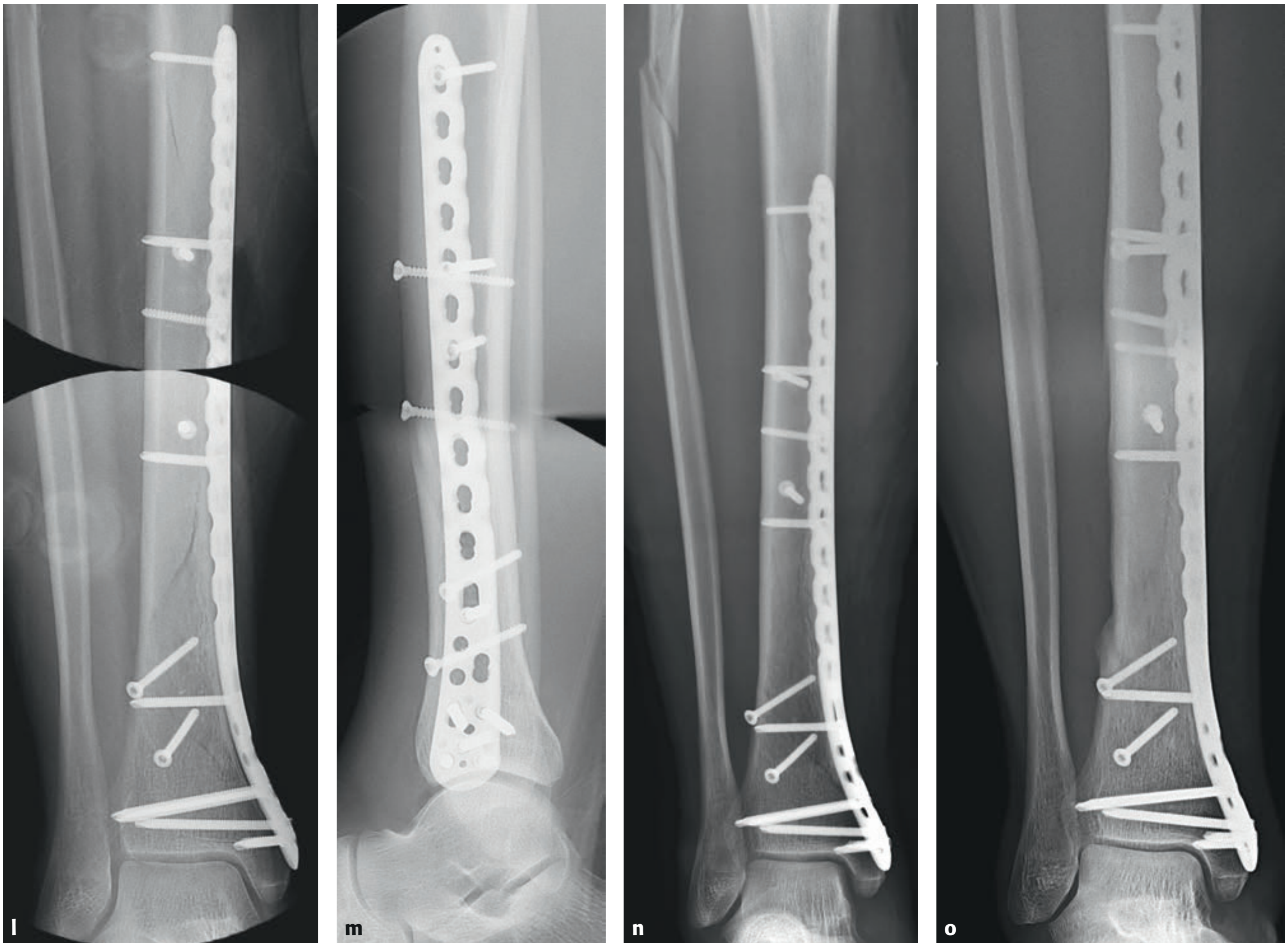


Fig 3.3.4-33a–o (**cont**) A 42B2 distal fracture treated with a compression technique with locking compression plate (LCP) in "hybrid" application.

l–n Then the inserted plate preliminary fixed distally with a conventional screw to approximate the plate close to the bone. Next, another conventional screw is applied at the proximal end of the plate which has to be centered perfectly in the lateral view. The well-aligned plate then is definitively fixed to the bone using LHS distally ("subbicortical" in the syndesmotic region) and proximally (bicortical). The one conventional screw at the proximal end of the plate is preferred to a LHS because it guarantees a tight fit of the plate to the bone, not irritating the soft tissues and it reduces the local stress to the bone thus decreasing the risk of later periimplant fracture.

o One year follow-up imaging.

By splinting fractures with plates, three main factors influence the stability of the fixation and the loading conditions of the plate-bone construct (**Table 3.3.4-3**, **Fig 3.3.4-34**):

- Length of the plate
- Working length of the plate
- Number, position, and design of the screws [6, 20]

4.5.1 Length of the plate

Bridge plate constructs are often long plates with few screws used to produce relative stability. A long plate improves the moment arm of the screws. This leads to a low pull out force acting on each screw which is especially helpful in osteoporotic bone (**Video 3.3.4-1b–c**). Utilizing a minimal invasive technique with subcutaneous or submuscular plate insertion, a long plate can be used without the need of additional soft-tissue dissection and devascularization. In general, the length of a plate depends upon the length of the fracture zone.

Empirically, the plate length should be two to three times the length of the overall fracture length in multifragmentary fractures and eight to ten times longer in spiral, oblique, or transverse fractures.

4.5.2 Working length of the plate

To avoid premature failure of a locking plate, the working length (length between the two screws bordering the fracture zone) should be optimized [20]. For a simple fracture pattern, when the gap size is small (< 1 mm) increasing the working length of a plate will minimize the chances of plate failure as the deformation of the plate under load (strain) will be small and distributed over a longer area and there will be load sharing with the fracture (**Fig 3.3.4-35**). In a situation with a short working length of the plate (no hole free at fracture level), the construct is stiff and the bone does not contact on the opposite side of the plate even under moderate loading. Load-sharing does not take place and maximal strain develops in the middle of the plate (**Fig 3.3.4-36**, **Video 3.3.4-5**). A longer working length of the plate decreases the stiffness of the construct and allows the small fracture gap on the opposite side of the plate to close, even with moderate loading. This brings the main bone segments into direct contact (**Video 3.3.4-6**). By further loading, the axial forces will be directly transmitted from one to the other main fragment without further strain on the plate (load sharing) (**Fig 3.3.4-37**).

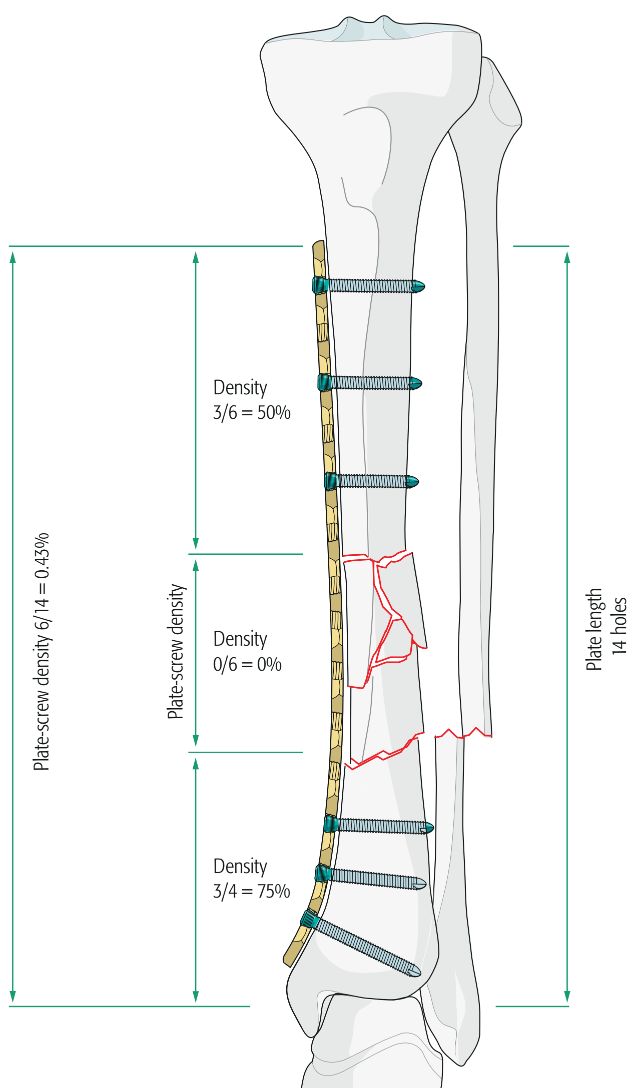


Fig 3.3.4-34 Importance of the plate-span ratio and plate-screw density in bridge plating technique. The schematic drawing shows a mechanically sound fixation of a multifragmentary diaphyseal fracture in the lower leg. The ratio between the length of the plate and the length of the fracture is known as the plate-span ratio. In this case, the ratio is high enough, ie, approximately 3, indicating that the plate is three times longer than the overall fracture segment. The plate-screw density is shown for all the three bone segments. The proximal main fragment has a plate-screw density of 0.5 (three of six holes occupied); the segment over the fracture has a density of 0 (none of four holes occupied); and the distal main fragment has a density of 0.75 (three of four holes occupied). The higher plate-screw density in the distal main fragment has to be accepted, since for anatomical reasons there is no way of reducing it. The overall plate-screw density for the construct in this example is 0.43 (six screws in a 14-hole plate).

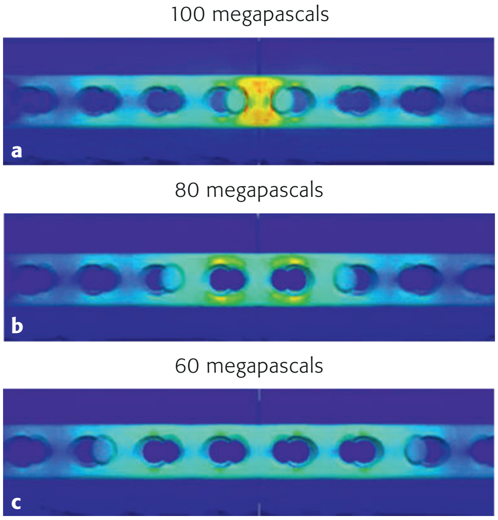


Fig 3.3.4-35a–c Short and long plate working length in a 1 mm gap model. The mean maximal von Mises stress in a 12-hole LCP 4.5 as a function of the bridging length (0–4 plate holes free) in a 1 mm gap model load-sharing situation (Karl Stoffel, MD, personal communication in 2003) **[21]**.

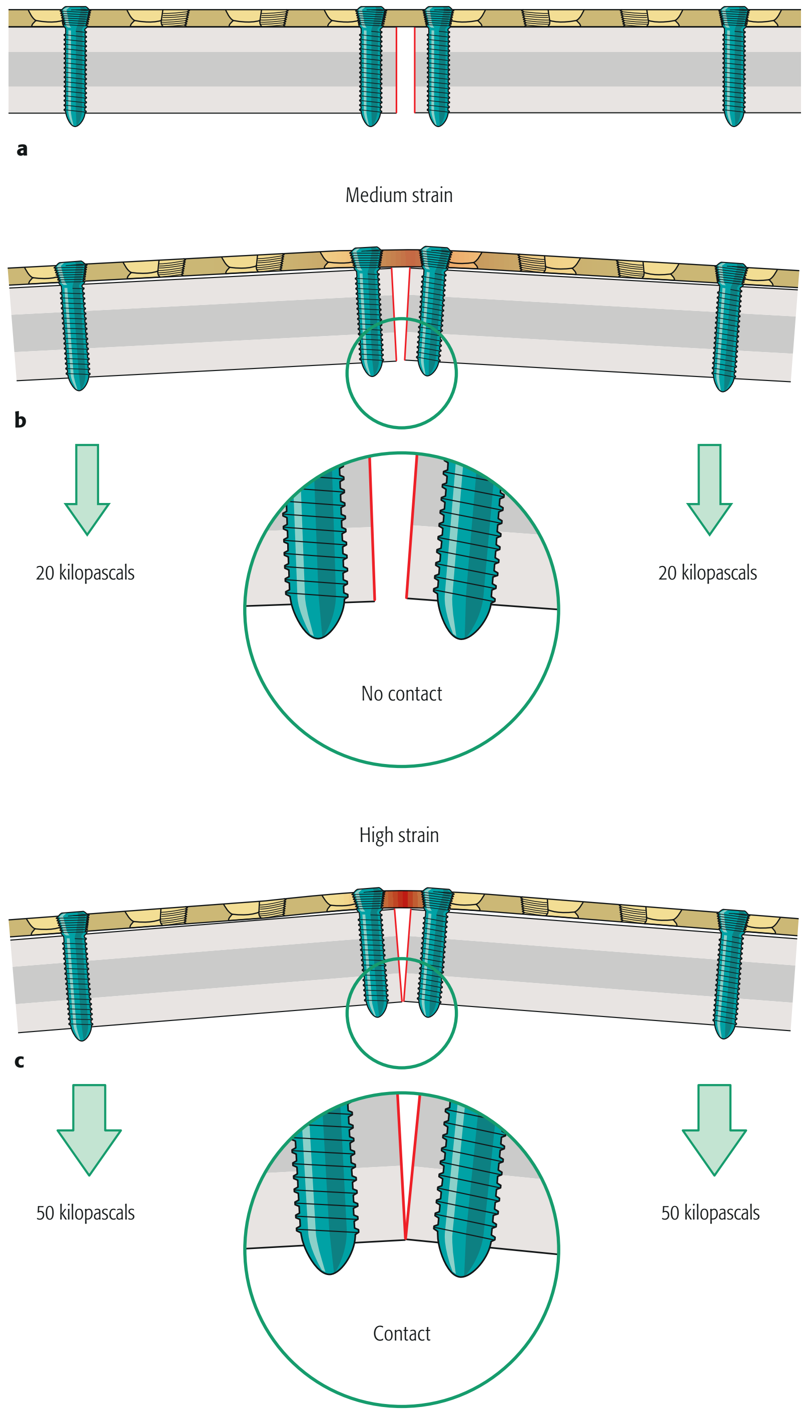


Fig 3.3.4-36a–c Short plate working length in a small gap model.

- **a** In a situation with shortest working length of the plate (no hole free at fracture level) the construct is stiff.
- **b** Therefore no bone contact on the opposite side of the plate will occur even in moderate loading.
- **c** Load sharing only takes place at high strain. This situation must be avoided as plate failure before fracture union is likely.

Video 3.3.4-5 High strain environment with small fracture gap.

Video 3.3.4-6 Low strain environment with small fracture gap.

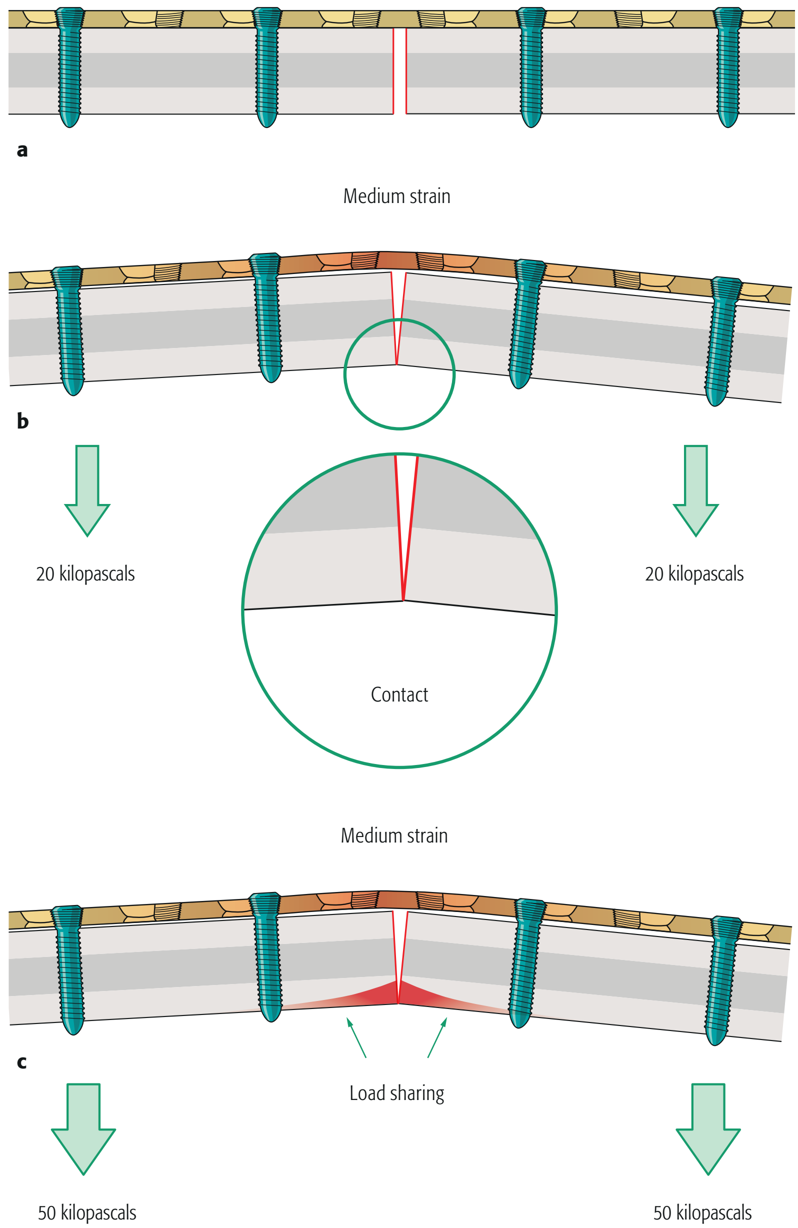


Fig 3.3.4-37a–c Long plate working length in small gap model.

a The longer working length segment at the fracture level decreases the stiffness of the construct.

b Even by moderate loading, the small fracture gap is closed on the opposite side of the plate quite easily which brings the main bone segments into direct contact.

c By further loading the axial forces will be directly transmitted from one to the other main fragment without further strain onto the plate (load sharing).

When the gap size is large, which is present in multifragmentary fractures or poorly reduced simple fractures, no direct bone contact occurs even under high load. Therefore, load sharing, which helps protect the plate against failure, does not happen. The strain on the plate is high under loading and even gets higher when the working length of the plate is increased by leaving more plate holes free at the fracture level (**Fig 3.3.4-38**). The lowest strain in the plate occurs when the screws are as close as practical to the fracture [21] (**Fig 3.3.4-39**). By placing the screws farther from the fracture, higher strain occurs in the free plate segment as well as in the screws (especially close to the fracture) and the screw-bone interface (**Fig 3.3.4-40**). Implant failure becomes more common.

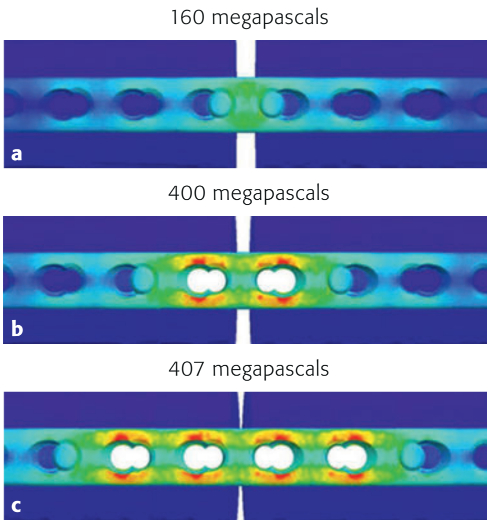


Fig 3.3.4-38a–c Short and long plate working length in 6 mm gap model. The mean maximal von Mises stress in a 12-hole LCP 4.5 as a function of the bridging length (0–4 plate holes free) in a 6 mm gap model. No load-sharing situation (Karl Stoffel, MD, personal communication in 2003) **[21]**.

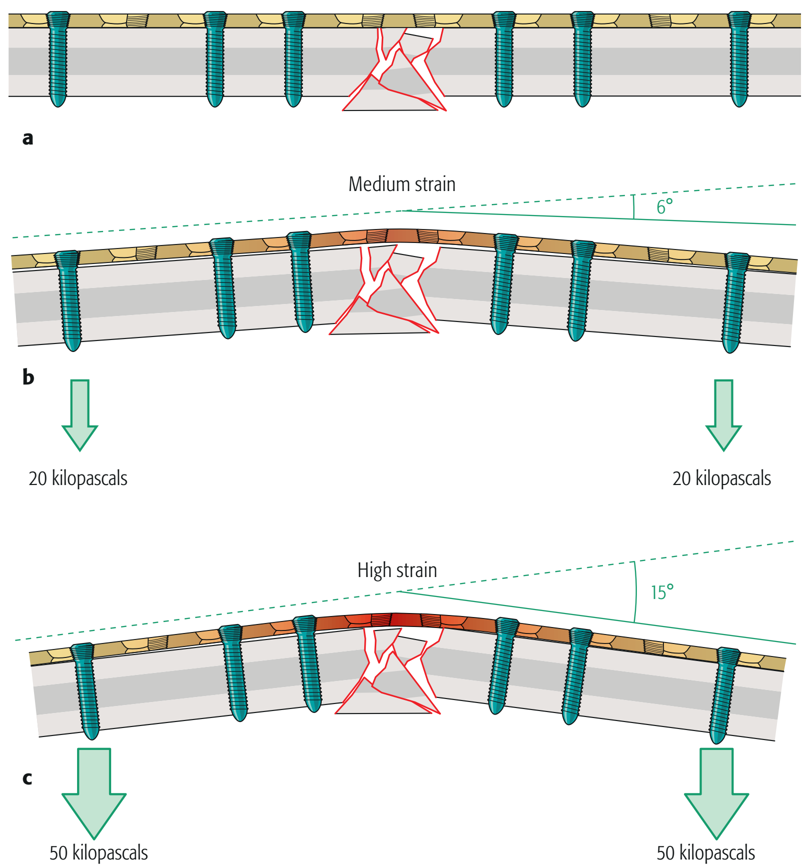


Fig 3.3.4-39a–c Short plate working length in a comminuted fracture or large gap model. The drawn angles are intentionally oversized for better graphical demonstration and understanding.

- **a** In comminuted fractures there will never be direct contact of the main fragments on the opposite side of the plate (no load sharing). Placing the screws as close to the fracture as possible will reduce the flexibility of the construct to a desired limit.
- **b** Under minimal loading (20 kilopounds, simulating partial weight bearing), the plate experiences minimal deformation.
- **c** Under higher loading (50 kilopounds, simulating half-body weight), the plate experiences more deformation.

4.5.3 Technique of bridge plate application using locking compression plate

Conventional or locking screws can be used successfully with LCP to produce a bridge plate and relative stability. In the upper extremity, especially the humerus, where high torsional loads are expected, LHSs can be added for better resistance against rotational forces. In lower extremity injuries, minimally invasive plating techniques have become standard in the last two decades.

Locking head screws provide several advantages when short segments of bone need to be fixed and bone quality is poor, reducing the pull-out strength of conventional screws. For metaphyseal fixation, some of the new plate systems provide a guide block for the periarticular part of the plate. This ensures perfect screw trajectory (important for tight locking) in soft metaphyseal bone and an aiming jig for easier percutaneous screw application in diaphyseal bone. In good quality diaphyseal bone, conventional screws are usually effective (**Fig 3.3.4-41**). With an extremely long multifragmentary zone, even when the screws are placed as close to the fracture as possible, fixation may be too flexible with only a single plate. This results in a high-strain environment that leads to plate deformation or delayed healing or nonunion. In such a situation, it might be necessary to add a second plate on the opposite side of the bone (or alternatively: an external fixator until healing) (**Fig 3.3.4-42**).

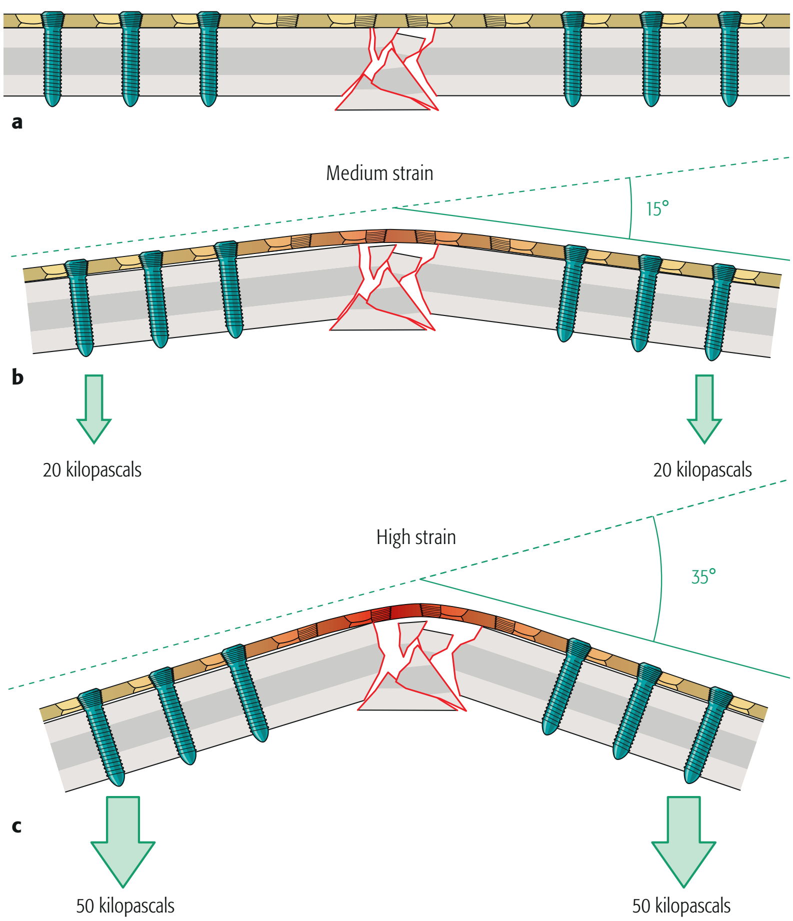


Fig 3.3.4-40a–c Long plate working length in a comminuted fracture or large gap model. The drawn angles are intentionally oversized for better graphical demonstration and understanding.

a By placing the screws farther from the fracture (compared to **Fig 3.3.4-39**), the construct becomes more flexible.

b Under minimal loading (20 kilopounds, simulating partial weight bearing), the plate becomes more elastically deformed compared to a situation with closer screws. It will be similarly deformed as in a situation with closer screws and higher loading, as shown in **Fig 3.3.4-39b**.

c Under higher loading (50 kilopounds, simulating half-body weight), the plate will be deformed much more and the mechanical axis will be even more separated from the plate resulting in more eccentrical loading. This results in even higher stress in the free plate segment as well as in the screws (especially those close to the fracture) which cannot be compensated with increased bridging length. Implant failure becomes more common. Therefore, the screws should be inserted as close as possible to the comminution.

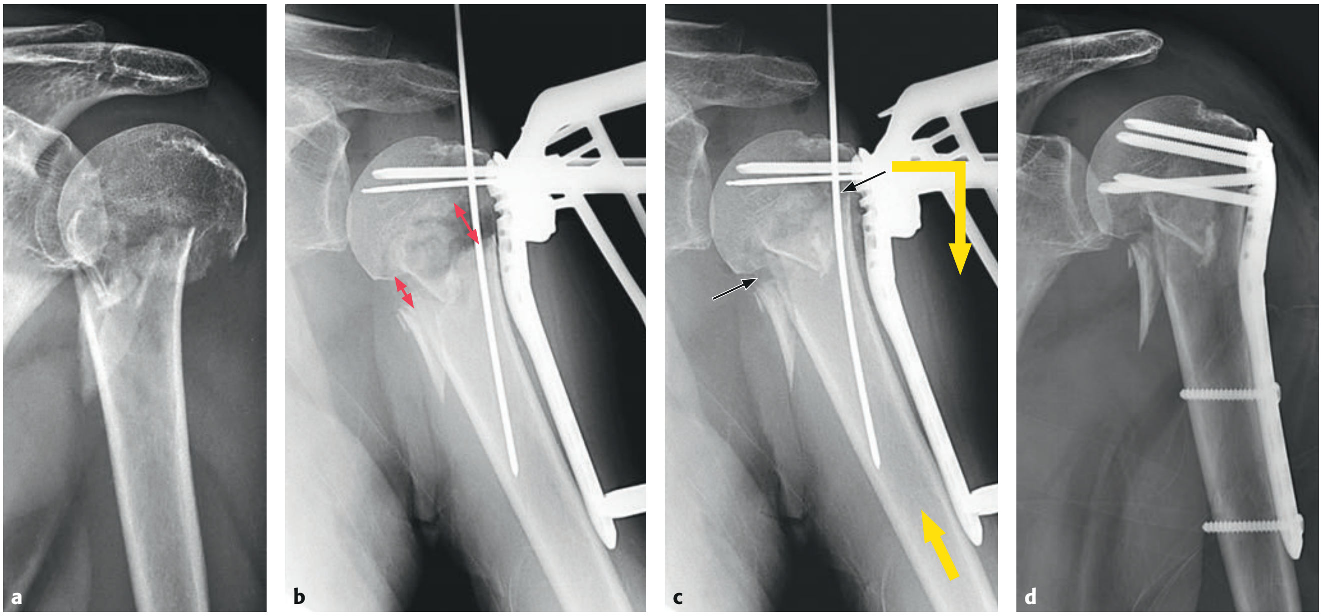


Fig 3.3.4-41a–e An 11A3 fracture treated with a bridging technique with PHILOS plate (MIPO).

- **a** An 84-year-old woman fell during skiing and sustained a subcapital humeral fracture with medial comminution.
- **b** After axial alignment and K-wire fixation, a PHILOS (5-hole plate) is inserted through a delta-split approach with the aiming jig. Preliminary proximal fixation is performed using a K-wire and one locking head screw. It is important to not fix the fracture in distraction (red arrows).
- **c** This must be reduced by slightly shortening the limb manually over the jig and the elbow (broad yellow arrows). Despite the medial comminution some buttress (anterior, posterior and/or central) can be achieved by this reduction manoeuvre (black arrows).
- **d** Only then are the diaphyseal screws placed. In good bone, as in this case with appropriate thickness of the cortex, conventional screws are sufficient. Using a 5-hole plate with a longer lever arm will allow the surgeon to use only two screws in the diaphysis. An additional screw close to the fracture in the distal fragment will provide more stability and reduce the risk of screw pull out.
- **e** One year follow-up image.

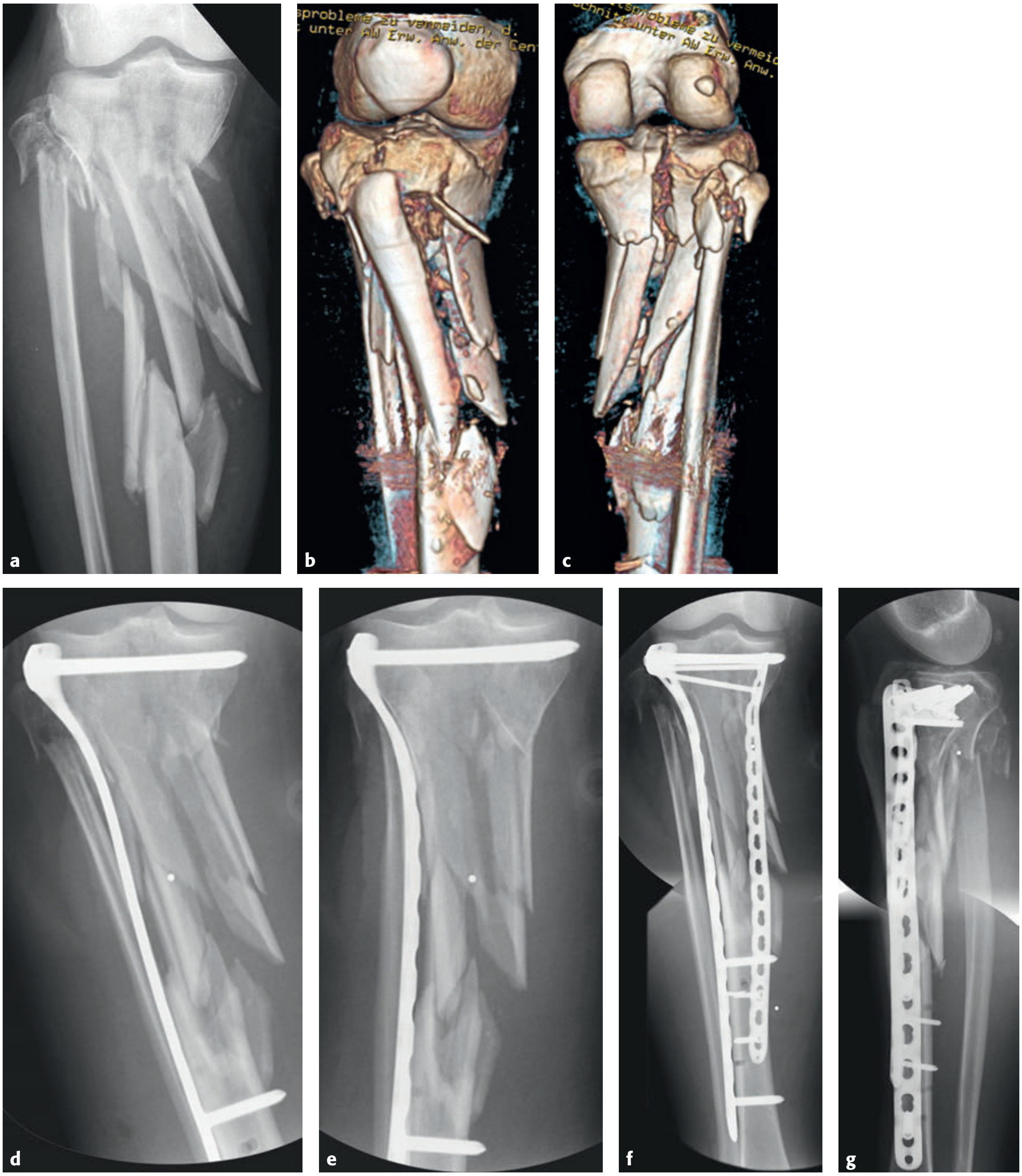


Fig 3.3.4-42a–k A 41C3.3 fracture treated with a bridging technique with two locking compression plates (LCP).

a A 36-year-old polytraumatized woman with bilateral proximal intraarticular tibial fractures after suicide jump off a bridge. She has a closed fracture which also manifests a compartment syndrome.

b–c Immediate knee-bridging external fixator and fasciotomy was followed by further imaging with computed tomography. Definitive stabilization on day 8 with minimal extraarticular proximal access medially and laterally.

d–g After reduction of the articular end block with K-wires as joysticks and a large King tong reduction forceps, the long LCP 4.5 L-plate was inserted submuscularly laterally and fixed with LHS proximally and percutaneously distally, as close as possible to the comminution zone. This construct is very flexible. This is captured intraoperatively and documented under image intensifier manually applying varus and valgus bending moments. This lateral plate alone could never withstand the physiological bending moments during the healing phase. A second medial bridging plate (LCP 3.5 straight, slightly contoured) is inserted percutaneously as well to protect the fracture from varus collapse. Due to the long-working length of these two plates and the comminution zone, relative stability is provided with indirect healing by callus formation.

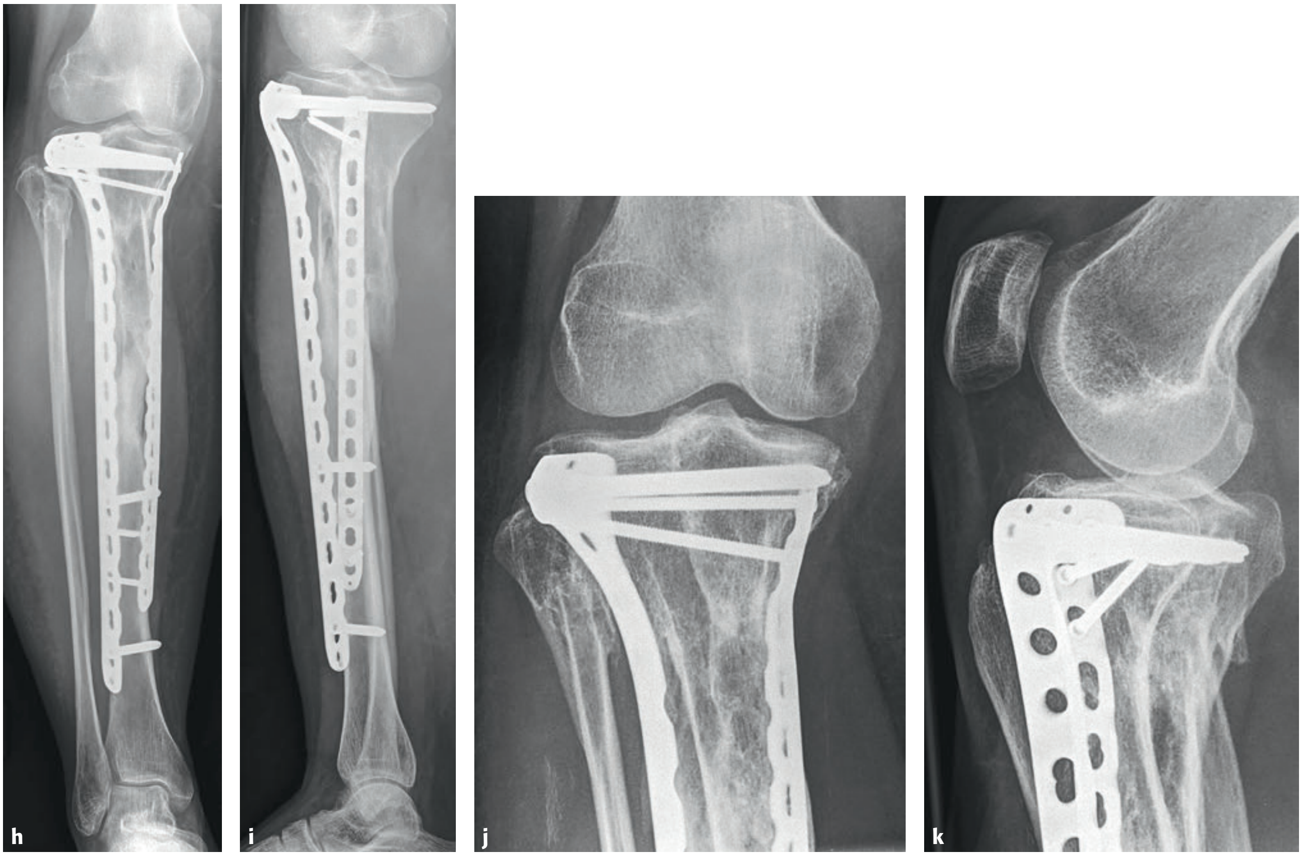


Fig 3.3.4-42a–k (**cont**) A 41C3.3 fracture treated with a bridging technique with two locking compression plates (LCP).
h–k Two-year follow-up images.

4.6 Locking compression plate for both absolute and relative stability

Combining two principles with one plate is reserved to combination type fractures in one bone, where one fracture is ideally fixed with absolute stability and the other fracture is best treated with relative stability. Two typical situations are:

- Articular fracture in combination with a multifragmentary metaphyseal fracture. These type C2 or type C3 fractures require anatomical reduction of the articular fracture and fixation with absolute stability while the multifragmentary metaphyseal (or diaphyseal) component is ideally bridged with minimal soft-tissue dissection and fixed with relative stability. Depending upon bone quality, the approach and reduction technique, LHSs alone or in combination with conventional screws may be used (**Fig 3.3.4-43**).
- Segmental metaphyseal-diaphyseal fracture with one simple and one multifragmentary fracture in a single bone. The simple fracture requires anatomical reduction and fixation with absolute stability while the same plate is used to bridge the multifragmentary part, providing relative stability (**Fig 3.3.4-44**).

The two different principles—absolute and relative stability—are incompatible in the same fracture zone, so these cases require careful preoperative planning and application of the AO principles. The adaptability of the LCP makes it an excellent implant for this type of complex fracture fixation.

4.7 Failure modes of locking plates

The LCP is a successful implant when used correctly but no implant has a 100% success rate and no fracture has a 100% union rate. The surgeon must be aware that because of the mechanical couple between the plate and the screw, the LCP has a different mode of failure than plates fixed with conventional screws. Cut out of the screws from the bone is less common and the risk of this complication can be reduced further by careful application of the plate using the principles and techniques described above. In general, monocortical screws should be avoided as should eccentric positioning of the plate on the diaphysis.

If fracture healing is delayed, there may be prolonged load bearing through the implant leading to metal fatigue with bending or breakage of the plate and/or breakage of the screws. The screws typically break at the junction between the plate and screw. Because all the screws need to fail simultaneously, cut out of the screws is less common. However, in osteoporotic bone or in patients with neuropathy, eg, those with diabetes, simultaneous failure of all screws at the bone-screw interface can result in severe instability, gross movement at the fracture site, and massive osteolysis due to bone destruction from the fixed screws moving like a "windscreen wiper" through the bone. Surgeons must be aware of this mode of failure as revision surgery can be difficult because of bone loss. If there are early signs of failure with osteolysis around the locking screws, patients must be followed up under close outpatient review and early revision surgery considered.

The second mode of failure that is less common with conventional screws is penetration of screw tips into the joint. Fixation of periarticular fractures in osteoporotic bone is challenging and the LCP is often the best implant. However, some implant loosening, loss of reduction and impaction (collapse) in osteoporotic, metaphyseal bone is common. In this situation, conventional screws placed in the subchondral bone often back out. However, this cannot happen with LHSs and so the tips of the screws may penetrate the joint. The proximal humerus and distal radius are the two most common sites for this complication. Frequently, the tips of the screw only penetrate 1–2 mm and remain within the articular cartilage and no damage ensues. However, these cases must be followed up closely and if the patient develops symptoms, such as pain or clicking, or radiological signs of chondrolysis, urgent removal of the screw is required. Remember, patients with neuropathy may not complain of pain.

Surgeons must also be aware that implant removal can be more difficult if the LHS is jammed in the thread hole of the plate. The risk of this problem can be reduced by the use of a torque-limiting screwdriver (which is mandatory) and ensuring that the correct guides are used so the screw joins the plate at the correct angle. The problem with jammed screws appears to be much more common with titanium implants as their biocompatibility allows bone ingrowth between the screw thread and the plate thread. Surgeons planning to remove LCPs must be aware of the different techniques available for removing jammed screws and have appropriate instruments available before surgery.

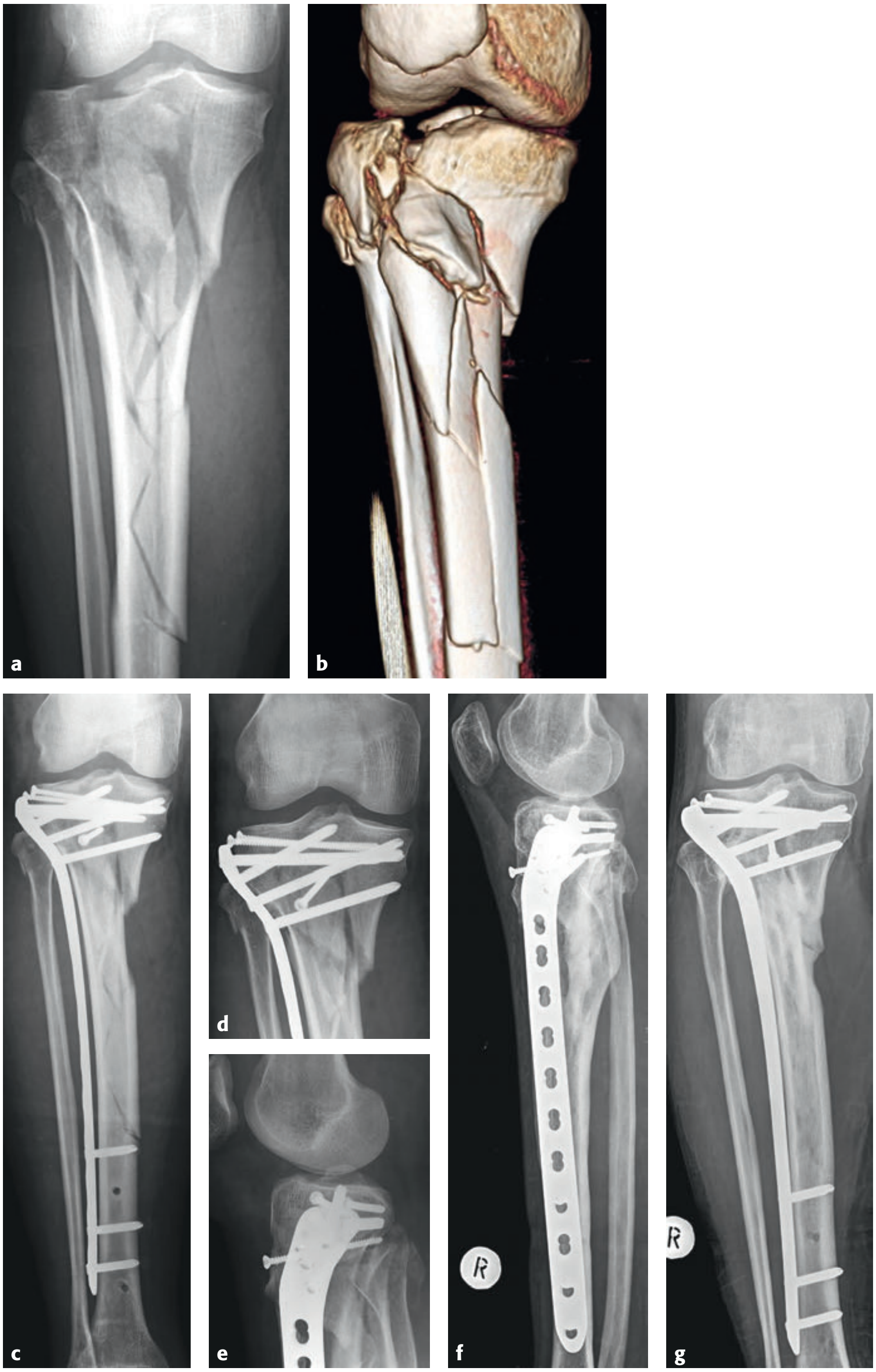


Fig 3.3.4-43a–g A 41C3.3 fracture treated with a combination technique with locking compression plate (LCP).

a–b A 39-year-old ski racer involved in a high-speed injury, with closed comminuted proximal tibial fracture with extension to midshaft. The patient also manifested a compartment syndrome. Initial step was a knee-bridging external fixator and fasciotomy.

c–e Main reconstruction with anatomical reduction and compression fixation of the proximal (articular) part using a lateral standard approach, followed by submuscular insertion of a long LCP-PLT. Proximal fixation with long "subbicortical" locking head screw (LHS) keeping the articular fragments in position as well as providing angular stability to prevent later medial collapse with varus deformity. Distally, LHS were applied percutaneously after final torsional and axial alignment in the sagittal plane has been checked clinically and under image intensifier. Primary bone healing occurred fast in the articular part; secondary healing was delayed but completed without further intervention.

f–g After 15 months the remodeling process was nearly finished.

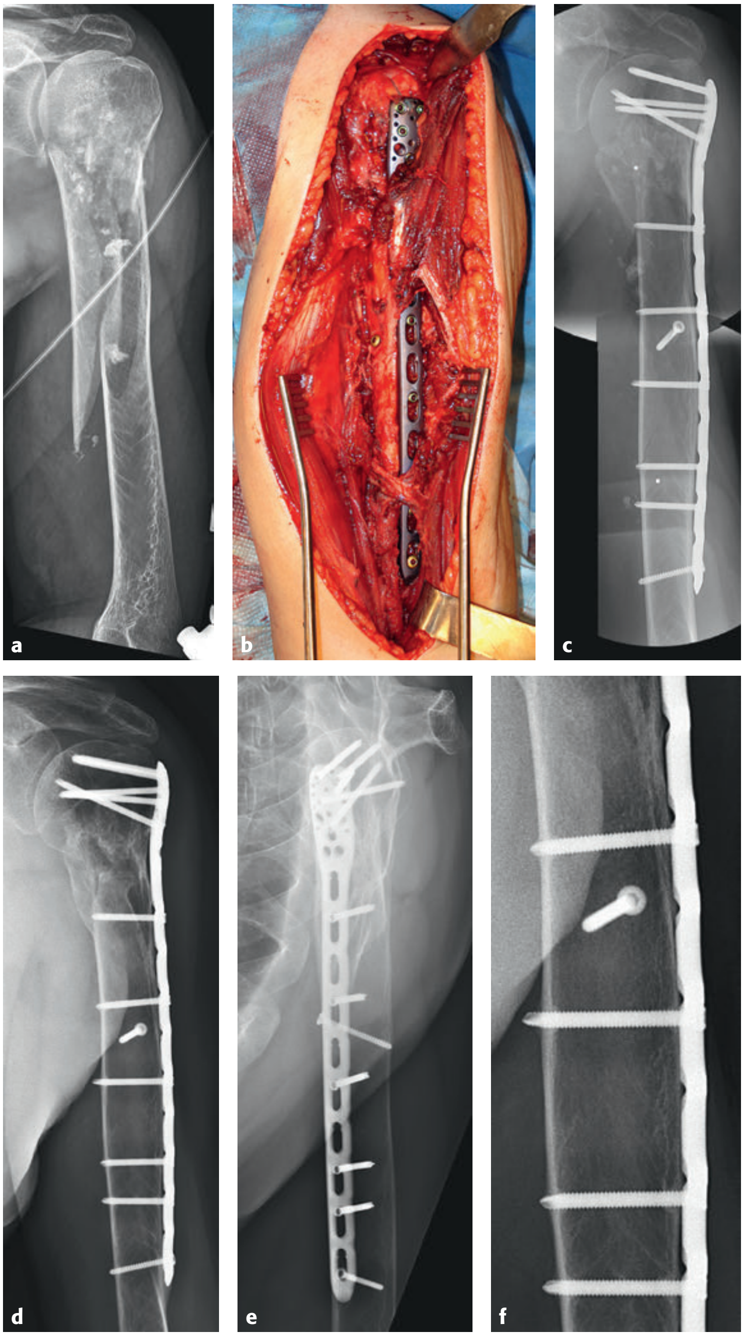


Fig 3.3.4-44a–f 11A2 and 12A1 fractures treated with a combination technique with locking compression plate (LCP).

a A 67-year-old man on a bicycle was hit by a car and sustained a segmental humeral fracture: subcapital multifragmentary fracture in combination with a simple torsional midshaft fracture. Severe osteoporosis was visible on x-rays.

b–c High stability was provided by perfect reduction of this long spiral fracture leading to a load-sharing construct. An open approach was chosen preserving the deltoid attachment and some perforating vessels in the splinted brachialis muscle. An anatomical reduction was achieved distally, retention by a lag screw (carefully tightened) and neutralization by a long PHILOS plate was performed. Due to the thin cortex, most screws used were bicortical locking head screw (LHS) except the most distal one. This cortex screw should reduce the stress on the bone at that level preventing a periimplant fracture in the future. The proximal fracture multifragmented block was biologically aligned and bridged with the plate using long LHSs in the head.

d–f After 2.5 years healing was uneventful, with primary healing distally and secondary osteopenia below the plate (stress shielding) and secondary bone healing with callus at the subcapital level.

5 Summary

The development and introduction of locking plate technology in the last 20 years has revolutionized operative fracture care. The use of LCPs requires a clear understanding of the principles governing their function. Use of angular stability, MIPO techniques, and hybrid screws allow applications that provide the optimum fracture stability for healing. Careful preoperative planning and precise surgical execution with LCPs using both conventional screws and LHSs provide correct plate length, working length, and screw type for the best fracture healing outcomes [22].

Classic references Review references

6 References

1. **Perren SM.** Basic aspects of internal fixation. In: Müller ME, Allgöwer M, Schneider R, et al. eds. *Manual of Internal Fixation*. Berlin Heidelberg New York: Springer Verlag; 1991:1–112.
2. **Perren SM, Buchanan J.** Basic concepts relevant to the design and development of the point contact fixator (PC-Fix). *Injury.* 1995;26(Suppl 2):1–4.
3. **Tepic S, Perren SM.** The biomechanics of the PC-Fix Internal fixator. *Injury.* 1995; 26(Suppl 2):5–10.
4. **Schütz M, Südkamp NP.** Revolution in plate osteosynthesis: new internal fixator systems. *J Orthop Sci.* 2003;8(2):252–258.
5. **Sommer C, Gautier E, Müller M, et al.** First clinical results of the Locking Compression Plate (LCP). *Injury.* 2003 Nov;34 Suppl 2:B43–54.
6. **Gautier E, Sommer C.** Guidelines for the clinical application of the LCP. *Injury.* 2003 Nov;34 Suppl 2:B63–76.
7. **Wagner M, Frigg R.** *AO Manual of Fracture Management, Internal Fixators, Concept and Cases Using LCP and LISS.* 1st ed. Stuttgart: Thieme; 2006.
8. **Bottlang M, Doornink J, Byrd GD, et al.** A nonlocking end screw can decrease fracture risk caused by locked plating in the osteoporotic diaphysis. *J Bone Joint Surg Am.* 2009 Mar 01;91(3):620–627.
9. **Gardner MJ, Griffith MH, Demetrakopoulos D, et al.** Hybrid locked plating of osteoporotic fractures of the humerus. *J Bone Joint Surg Am.* 2006 Sep;88(9):1962–1967.
10. **Stoffel K, Lorenz KU, Kuster MS.** Biomechanical considerations in plate osteosynthesis: the effect of plate-to-bone compression with and without angular screw stability. *J Orthop Trauma.* 2007 Jul;21(6):362–368.
11. **Staubli AE, De Simoni C, Babst R, et al.** TomoFix: a new LCP-concept for open wedge osteotomy of the medial proximal tibia—early results in 92 cases. *Injury.* 2003 Nov;34 Suppl 2:B55–B62.
12. **Egol KA, Kubiak EN, Fulkerson E, et al.** Biomechanics of locked plates and screws. *J Orthop Trauma.* 2004 Sep;18(8):488–493.
13. **Sommer C, Babst R, Müller M, et al.** Locking compression plate loosening and plate breakage: a report of four cases. *J Orthop Trauma.* 2004 Sep;18(8):571–577.
14. **Haidukewych GJ, Ricci W.** Locked plating in orthopaedic trauma: a clinical update. *J Am Acad Orthop Surg.* 2008 Jun;16(6):347–355.
15. **Tan SL, Balogh ZJ.** Indications and limitations of locked plating. *Injury.* 2009 Jul;40(7):683–691.
16. **Hunt SB, Buckley RE.** Locking plates: a current concepts review of technique and indications for use. *Acta Chir Orthop Traumatol Cech.* 2013;80(3):185–191.
17. **Bonyun M, Nauth A, Egol KA, et al.** Hot topics in biomechanically directed fracture fixation. *J Orthop Trauma.* 2014;28 Suppl 1:S32–S35.
18. **Takemoto RC, Sugi MT, Kummer F, et al.** The effects of locked and unlocked neutralization plates on load bearing of fractures fixed with a lag screw. *J Orthop Trauma.* 2012 Sep;26(9):519–522.
19. **Yi JW, Oh JK, Han BS, et al.** Healing process after rigid plate fixation of humeral shaft fractures revisited. *Arch Orthop Trauma Surg.* 2013 Jun;133(6):811–817.
20. **Claes L.** Biomechanical principles and mechanobiologic aspects of flexible and locked plating. *J Orthop Trauma.* 2011 Feb;;2 (Suppl 1:S4-S7.
21. **Stoffel K, Dieter U, Stachowiak G, et al.** Biomechanical testing of the LCP—how can stability in locked internal fixators be controlled? *Injury.* 2003 Nov;34 Suppl 2:B11-19.
22. **Ricci WM.** Use of locking plates in orthopaedic trauma surgery. *JBJS Rev.* 2015 Mar 17;3(3):pii: 01874474-201503030-00003.

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