A. INTRODUCTION

Orthopaedics is a highly technical specialty that employs an incredibly broad range of techniques, from fine microvascular surgery to bone fixation implants, to large metallic and polymeric composite implants for joint replacement, to sophisticated methods of external fixation involving all regions of the skeleton. Successful use of these implants and devices requires sophisticated technical knowledge on the part of the surgeon, as well as respect for the biology of the tissues being handled, for the best chance of a successful result. The surgeon must be certain that the indications for surgery are appropriate and that the patient is suitable for the operation: Even the best-performed procedure will fail if the indications are not correct and if the patient cannot benefit.

The technical aspects of applying internal and external fixation implants are critical to achieving bone union in the appropriate position and to avoiding implant failure. It is essential that resident and neophyte surgeons master the general principles and that mature surgeons constantly remind themselves of them, particularly when they are employing fixation techniques that they do not perform often.

METALLIC ALLOYS

The biocompatibility of metallic alloys is based on the presence of a constituent element that has the ability to form an adherent oxide coating that is stable and chemically inert. Materials that do not form stable oxides or that permit the oxide to become detached from the underlying metal, such as common carbon steel, are not biocompatible and continue to
undergo degradation in the body. The common metallic alloys [e.g., cobalt chromium (ASTM F75-82, ASTM 799-82), titanium alloy (ASTM F136-79), and stainless steel (ASTM F55, F56)] have at least one element that forms an adherent oxide coating. The composition of these alloys is shown in Table 11.1. Detailed specifications of the composition are given in the American Society for Testing and Materials (ASTM) standards.

Composition varies somewhat depending on the intended use of the material. For example, if ductility is not a requirement, carbon is used to strengthen cobalt-chromium alloy (F75-82), although carbon reduces the alloy’s ductility. Other phases present in each alloy tend to stabilize the crystal structure. Forged cobalt-chromium alloy is strengthened by nitrogen as a minor impurity. Certain elements are deleterious to the properties, such as oxygen in a titanium alloy, which tends to make it brittle. Similarly, carbon in stainless steel decreases ductility unless it is allowed to precipitate in the grain boundaries as chromium carbide, where it decreases resistance to corrosion.

Implant alloys are manufactured by melting the appropriate elements together to produce a liquid solution that subsequently becomes a solid solution of each element in the matrix after cooling. This material is shipped as a bar, rod, or plate for further processing by the implant manufacturer. Titanium alloy can be shaped by machining from bar stock or sheet stock; stainless steel implants can be produced the same way. After initial forming of the more ductile version of the cobalt-chromium alloys, forging significantly strengthens the alloy and brings it to its final shape by applying mechanical work. The casting process can be used for titanium alloy or cobalt-chromium alloy to produce intricate shapes. A wax mold of the prosthesis is coated with ceramic and fired. The wax melts out of the ceramic mold (i.e., lost wax process); after cooling, liquid metal is poured into the ceramic shape and allowed to solidify. Final shaping is done by machining and grinding. Machining and forging done under appropriate conditions do not diminish the mechanical properties of the alloy. However, investment casting typically weakens the material by causing an increase in the grain size. This mostly affects the fatigue life, because for most materials the fatigue strength is inversely proportional to grain size.
MECHANICAL PROPERTIES OF IMPLANT MATERIALS

The yield stress is the transition point between elastic deformation and plastic or permanent deformation. Deformation at strains lower than this level obey Hook's law, which states that the elastic modulus (Young's modulus) is the proportionality constant in the linear portion of the stress-strain curve below the yield point. Fatigue strength refers to the ability of a material to resist repetitive loading. Typical yield and fatigue strengths and elastic moduli are presented in Table 11.2.

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield (MPa)</th>
<th>Fatigue (MPa)</th>
<th>Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoCr (cast)</td>
<td>518</td>
<td>255</td>
<td>221</td>
</tr>
<tr>
<td>CoCr (forged)</td>
<td>890</td>
<td>759</td>
<td>221</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>863</td>
<td>552</td>
<td>110</td>
</tr>
<tr>
<td>Stainless steel 316L</td>
<td>241</td>
<td>180</td>
<td>193</td>
</tr>
</tbody>
</table>

Table 11.2. Typical Yield and Fatigue Strengths of Metal Alloys Used in Orthopaedic Surgery

The elastic modulus is an intrinsic property of a material generated by the attraction of atoms within the material, and it has essentially no variation with thermal or mechanical history. Fatigue strength, however, can be significantly improved or diminished by heat treatment. Cast cobalt-chromium alloy has a fatigue strength of about 255 megapascals (MPa), which is only about twice that of the cast stainless steel used in total hip prostheses in the early 1970s that failed in fatigue. Titanium alloy, although quite strong in fatigue strength in the “as received” or forged condition, can undergo significant deterioration of its fatigue properties as a result of applying a porous coating. Failure is caused by the creation of stress concentration sites by the porous coating, and the grain growth caused by the heat treatment used to apply the porous coating. Much of the deterioration in properties of titanium alloy can be alleviated by the use of a diffusion bonding process that lowers the temperature of sintering. The notch sensitivity problem is managed by design modifications that remove the porous material from areas subjected to tensile loading. These concerns regarding the effect of porous coating do not apply to implants for internal fixation.

Surface hardness is tested by indentation tests, such as the Rockwell test or the Vickers test, in which the material is indented by a very hard object. The resistance to this plastic deformation indicates the tensile strength of the material and its wear properties. These tests are suitable for metallic alloys.

STAINLESS STEEL VERSUS TITANIUM FOR BONE FIXATION IMPLANTS
For decades, stainless steel has been the most widely used material for bone fixation implants. The 3.16L alloy is still used most commonly; however, other stainless steel alloys are also in use and provide useful characteristics such as increased strength in hip fixation implants, which can be subjected to high bending loads and fatigue stress because of delayed healing (Table 11.1). A major concern about stainless steel implants has been their stiffness, which is approximately seven times that of human bone. Uhthoff and Dubus (103) and others (16,27,63) have demonstrated in animal experiments that when rigid internal fixation is applied with stainless steel implants, prolonged exposure of the bone can lead to porosis and weakening of the bone due to stress protection. This is also seen in total joint arthroplasty, particularly about the proximal portions of the stem in the femoral components of total hip arthroplasty. Perren et al. (81,82) have shown that the porosity and weakening observed is in part due to the revascularization response resulting from the surgical procedure itself; in spite of this, however, stress protection remains a significant problem, particularly where the size and stiffness of the implant is significant compared to that of the bone. Chapman et al. (27), in a review of 174 forearm fractures, found no refractures of the radius or ulna after removal of AO 3.5 mm dynamic compression (DC) plates, whereas in all three patients in whom the larger narrow DC plates and 4.5 mm screws were used, refractures occurred either through the screw holes or the fracture site.

Therefore, orthopaedic surgeons have sought a material for plates and nails that is closer to bone in its mechanical characteristics, yet would be stiff enough to permit fracture healing and strong enough to avoid fatigue failure prior to fracture union. Titanium and its alloys, widely used in military aircraft and submarines, have proven, in part, to meet this need. Most manufacturers have used a titanium alloy containing 6% aluminum and 4% vanadium (6-4 titanium). The mechanical characteristics of commercially pure (CP) titanium were not suitable for internal fixation implants until recently; however, the AO group has used plates and screws of CP titanium, which have proven to be clinically useful. By utilizing particular forging and other techniques, they have been able to render the CP titanium sufficiently strong. Other alloys of titanium, particularly beta alloys, offer even better mechanical properties for internal fixation implants than the 6-4 titanium, and some of these are listed in Table 11.1. Overall, titanium alloys are approximately twice as flexible as stainless steel and at least one-third stronger. A primary disadvantage of titanium is that it is difficult to manufacture, which increases costs. Also, it is more brittle than stainless steel: Cracks occurring from notches in the metal tend to propagate much more easily than in stainless steel, which influences implant design and how the surgeon uses the implants. Titanium alloys become particularly useful in smaller implants, such as nonreamed intramedullary nails, and in smaller plates, which employ smaller-diameter screws, where the superior strength of the titanium results in much less screw and nail breakage compared with stainless steel. In spite of the increased cost, most major implant manufacturers today offer bone fixation implants composed of titanium. Some entire implant systems, both plates and intermedullary nails, are offered in titanium.

In addition, titanium is more resistant to corrosion than stainless steel, which has a tendency to experience crevice corrosion at the contact point between screw heads and plates. Plate failure can take place through these corrosion pits. Titanium aggressively forms an oxide, which provides superior passivation of the implants. I have removed...
numerous titanium plates and screws and have never seen any visible evidence of crevice corrosion.

All metallic implants release a small quantity of metallic ions into the local soft tissues and general circulation. Although concerns have been raised about the potential toxic or carcinogenic effects of these minute amounts of ions, and sarcomas have been described in association with implants, no evidence has been presented that implants are a significant health risk to patients. On the other hand, current implant materials have been used for approximately 60 years. Whether exposure to these implants for up to 80 or 90 years in our long-lived population will produce diseases is not yet known. When placing these implants in children and young adults, a discussion with patients and their parents regarding this issue is appropriate. If concerns are expressed after implantation, and removal of the implant will not incur unacceptable risks, then removal is usually advised.

**IMPLANT POLYMERS**

Four polymers find application in orthopaedic surgery on a routine basis. These are ultrahigh-molecular-weight polyethylene (UHMWPE), polypropylene, polytetrafluoroethylene (PTFE, Teflon), and polymethylmethacrylate. Other polymers show promise as matrix materials for composite biomaterials, including polysulfone (UDEL), polyethersulfone, and polyetheretherketone (PEEK). Their chemical structures are shown in Fig. 11.1.

![Chemical structures of implant polymers](image)

Polymers are manufactured under heat and pressure to produce addition or condensation reactions. Condensation reactions produce polymers by a combination of an organic acid and an organic base to produce water or an alternative third compound (Fig. 11.2). Reactive moieties on both ends of each type of molecule permit the reaction to grow long chains. Additional polymerization produces the polymer chains by adding one more link to a chain that was begun by an initiator molecule reacting with a carbon double bond, such as found in ethylene. Most implant polymers are thermoplastic, because they can be melted and cooled until solid again with no composition change.
Although injection molding of polymers from the melt is possible, molding of granules of a polymer under heat and pressure, called compression molding, is more common for production of polyethylene components. Machining of implants from stock is another technique that can be used. Both methods produce acceptable articular surfaces for implants.

The uses for polymeric materials are more diverse than for metallic implants, but their interchangeability is not as great. Polypropylene is used as a ligament augmentation device for knee reconstructive surgery, UHMWPE is used as the bearing surface in total joint arthroplasty, and Teflon is expanded to form a Gore-tex material used in knee reconstructive surgery. Polymethylmethacrylate is partially polymerized, provided as granules, and combined with monomer and an initiator to form a final polymerized mass (e.g., Zimmer bone cement). When copolymerized with polystyrene, polymethylmethacrylate is used in a similar manner to form Simplex-P (Howmedica, Rutherford, NJ).

Polylactic and polyglycolic acids, polyglactin (copolymers of the two acids), and polydioxanone find their main uses as resorbable suture materials under the brand names Dexon (Davis and Geck; US Surgical, Norwalk, CT), Vicryl, and PDS (both manufactured by Ethicon, Johnson and Johnson, Somerville, NJ). These materials are also available as resorbable pins, primarily for fracture fixation in the hand, foot, ankle, and skull (3). These materials can be made relatively stiff and are slow to resorb. Polylactic acid is now available as screws and pins because its slow rate of resorption may reduce the level of inflammatory response. Attempts at improving the stiffness of polylactic acid have included mixture with hydroxyapatite fibers.

CERAMICS

A ceramic is a nonmetallic, nonorganic material, usually produced by high-temperature processing. Typically, ceramics have high thermal and electrical resistance and high elastic modulus, low ductility, and low tensile strength. Excellent biocompatibility results from chemical inertness.

Carbon (Pyrolite) is produced by deposition of carbon from a gas-phase breakdown of gases such as methane (CH₄) or methyltrichlorosilane (CH₃SiCl₃) to produce carbon-silicon...
compounds with various proportions of silicon, typically 10% to 20%.

Ceramic materials are characterized by very high strengths, but brittle failure occurs after minor plastic deformation. Although the failure strength is quite high in many cases, relatively low failure stresses can occur occasionally.

Attempts have been made to form plates from ceramics, but they have not proven practical because of the inability to conform them to the bone, and because of their high failure rate caused by their brittle nature. Because of the unique characteristics of ceramics, they enjoy much more practical application in the bearing surfaces of total joint replacement prostheses and in the coatings of prosthetic implants where direct bone–implant ingrowth is desired.

**COMPOSITE MATERIALS**

A composite is a combination of two or more materials in which the mechanical performance of the composite is superior to that of either component alone. In man-made composites, usually one component is a fiber and the other is a matrix material. Bone itself achieves most of its mechanical properties as a natural composite material composed of calcium phosphate ceramics in a highly organized collagen matrix.

The first composite to come into general use, initially made by an orthopaedic surgeon, was the plaster of Paris bandage. This has been refined to fiberglass with a polymeric matrix in the current synthetic casting materials. A composite for internal prosthetic applications is based on the addition of chopped carbon fiber to improve the mechanical properties of polyethylene components.

Materials used in composites intended for implantation must be biocompatible. Three potential matrix materials that have undergone at least preliminary biocompatibility studies are thermoplastic and have similar structures (Fig. 11.1). These are UDEL, polyethersulfone, and PEEK, discussed above. The fiber materials strengthen and stiffen the matrix and can be used as chopped fibers or as long fibers. The chopped fiber material usually produces a composite that is isotropic, having stiffness and strength properties that do not vary with direction. The long fibers can be woven, wound, or formed in many geometric orientations to provide desirable mechanical properties. Only carbon fiber is being studied for orthopaedic applications.

Composite structures are typically produced from laminates. A laminate is a thin sheet of composite material in which all the fibers run in one direction and are held together by a thin coating of the polymer matrix material. It is produced by passing the fibers through the polymer, allowing it to be coated, and subsequently sticking the layers together and pressing them. This laminate is combined with other laminates to form a bulk composite; the properties of this composite vary depending on the orientation of each layer of the laminate. The primary direction of the fibers is called the zero direction, and other layers, or laminae, are oriented in relation to this (e.g., 0°, 45°, -45°, 90°, +30°, and -30°) to vary the properties of the polymer. A polymer that has equal numbers of layers in the 0°, 45°, -45°, and 90° orientations is called a pseudoisotropic polymer because the mechanical properties in any
direction in the fiber plane are the same. An alternative means of producing a composite structure is to wind one or more continuous fibers in a particular orientation to form the desired prosthetic shape.

The mechanical properties of primary concern are the strength and the modulus. The strength generally mirrors the modulus, and both of these depend on the orientation of fibers. The elastic modulus can be estimated for laminated structures from the two “rules of mixtures.” The modulus parallel to the fibers \( E_{\text{parallel}} \) is proportional to the amount of fiber in a simple linear relationship:

\[
E_{\text{parallel}} = E_f V_f + E_m V_m
\]

in which \( E_f \) and \( E_m \) are the moduli of the fiber and matrix, respectively, and \( V_f \) and \( V_m \) are the volume fractions of the fiber and matrix, respectively. In the range of typical polymer fiber used in a laminate of 0.4–0.7 volume fraction fiber, the elastic modulus varies linearly in that range parallel to the fibers. The modulus relationship perpendicular to the fibers is more complicated and less applicable to all composites:

\[
E_{\text{perpendicular}} = \frac{E_f E_m}{(E_f V_m + E_m V_f)}.
\]

Because carbon fiber polymeric materials are strong and radiolucent, roentgenographic examination of fractures fixed with external fixation devices made of these materials can be performed with relative ease. Similarly, halo rings made of these materials are compatible with magnetic resonance imaging, allowing studies of the brain and cervical cord to be performed.

Plates and intermedullary nails manufactured from carbon composites have been used experimentally for internal fixation. Their potential advantages include radiolucency (making observation of fracture healing easier), the ability to vary the modulus of the material, and the potential for using an absorbable polymer. None of these materials are currently in clinical use because of the inability to modify the shapes of the implants intraoperatively to fit the bone; because of liberation of carbon fibers into the adjacent tissues; and because the difficulties of predicting the resorption of polymers in larger load-bearing implants, as opposed to screws and pins, has thus far precluded their use for these larger implants. No doubt, implants in this category will be available in the future, perhaps even containing bone inductive proteins.

**B. PRINCIPLES OF WIRE, CABLE, AND PIN FIXATION**

In France in the late 18th century, brass and iron wires were used for fracture fixation. Later, silver wire was introduced by Lister to treat a patellar fracture. Parham and Martin (77) described steel bands used around the shaft of fractured long bones in 1913, and in 1922 Johnson developed stainless steel, which is the material still used for most types of wire and pin fixation. This form of fixation includes fine Kirschner wires, larger Steinmann pins, and flexible wire used for provisional and definitive fracture stabilization, osteotomy fixation, and skeletal traction.

**KIRSCHNER WIRES**
MATERIAL FEATURES

Martin Kirschner (1879–1942), a surgeon from Heidelberg, Germany, was the first to use thin wire pins for fracture management, in 1909. Kirschner, or K-wires are manufactured in lengths from 7 to 31 cm and in diameters from 0.6 to 3.0 mm. They may be smooth or threaded, but threaded wires have poorer bending strengths for a given pin diameter and may be difficult to remove at a later date. The wire may be pointed at one or both ends. In the latter case, the pin can be inserted antegrade from the fracture site to exit from the distal fragment and then retrograde back into the proximal fragment. K-wires may be trocar or diamond pointed (Fig. 11.3). The trocar point is somewhat easier to insert into dense cortical bone and there is less of a tendency to overheat.

Because of their flexibility, K-wires are normally introduced with a power drill and a pin stabilization system, which may be a telescopic guide attached to the end of the drill chuck, or an external guide with a handle. The drill itself may have the capability of rapid locking and release of the wire; advancement therefore can be made from the barrel of the drill, which acts as the guide. Small-diameter pins can be inserted through large bore needles. An alternative is to introduce a gentle bow into the wire while drilling. This prevents oscillation of the wire. Two disadvantages of this technique are that the direction of the wire may be more difficult to control and the wire will overheat more rapidly. When K-wires are used, wire cutters and instruments for wire bending are required. The wire benders may be simple metal tubes into which part of the wire is inserted before being manipulated, or special pliers can be used (Fig. 11.4).
INDICATIONS FOR USE

**Traction**

K-wires, even those with 3 mm diameters, are quite flexible, but the wire may be stiffened by applying tension with a traction bow. The construct is thus made strong enough to apply a load of approximately 20 kg, providing the bone is able to sustain this weight (Fig. 11.5).

*Figure 11.5. Kirschner wire tensioner and traction bow.*
K-wires are frequently used for the application of skeletal traction, particularly in children, in whom smaller traction loads are required and the cosmetic advantages of a smaller skin entry point pertain. K-wires can be used in any of the common sites for skeletal traction in the treatment of extremity fractures such as the upper end of the tibia, the lower end of the femur, the olecranon, and the digits. In children, passage of traction pins across the upper tibia risks damage to the physis, resulting in its partial closure and a subsequent growth deformity. If the proximal tibia must be used, the wire must be inserted posterior and distal to the physeal line.

For a given load on the traction system, the force per unit area directed against the bone by the K-wire is greater than that exerted by a larger-diameter pin. Osteopenic bone is therefore a relative contraindication to use of a K-wire for traction. See Chapter 10 for additional details.

**Provisional Fixation**

An important principle of internal fixation of fractures, especially in the presence of comminution, in which the definitive fixation of two fragments may impede the subsequent reduction of the rest of the fracture, is that the fracture be initially provisionally fixed. K-wires are particularly useful, and many of them may be used in combination, with little damage to the bone or its vascularity. They may be used alone or in combination with bone-holding forceps or cerclage wires. A complicated fracture can be fully and accurately reduced and temporarily fixed with K-wires. Radiographs may then be taken on the operating room table to demonstrate the anticipated result or to demonstrate any defects in the reduction and facilitate their correction (Fig. 11.6).

Careful planning is required during insertion of provisional K-wire fixation to prevent the wires from interfering with the later exchange to the definitive fixation with, for example, plates and screws. Where K-wires are to be replaced by lag screws, introduce the wires in the same direction that will be used later for the screw fixation. Nonparallel K-wires will interfere with production of satisfactory compression by lag screws across the fracture site.
(Fig. 11.6). If crossed wires must be placed, remove them after the screw is in place and before final compression. A simple trick to facilitate plate application in the presence of multiple K-wires is, first, to place the plate on the bone and mark the location of the holes on the bone with a marking pen. Then, insert all the K-wires through the location of the holes.

**Definitive Fixation**

K-wire fixation can be employed successfully where the subsequent loading on a fractured bone is anticipated to be small because the fracture is close to a joint or if the overall length of the bone is not great. Thus, intra- and extraarticular fractures of the phalanges, metacarpals, and metatarsals, and other bones of the carpus, tarsus, and distal radius, may be stabilized with crossed Kirschner wires.

- Insert the first K-wire at right angles to the fracture plane.
- Compress the fracture fragments and place a second K-wire obliquely to lock and maintain the compression (Fig. 11.7). In the fixation of transverse phalangeal fractures, it has been found that four crossed wires provide the strongest fixation; and in oblique phalangeal fractures, three wires at right angles to the fracture provide the best stabilization (106). Stabilization with K-wires in these cases must almost always be supplemented and protected by plaster-cast fixation, but early motion is important.

Another common use for K-wire fixation is in supracondylar fractures of the humerus in children: After closed or open reduction, two K-wires inserted from the lateral side can maintain good reduction when combined with external cast immobilization (see Chapter 164).

If K-wires are used for definitive fixation and the proximal end of the wire is left straight,
there is a significant likelihood of migration of the wire into or from the bone. Therefore, the exposed end of the wire should always be bent with an appropriate instrument if it will be left buried. If only a very small segment of the wire is left exposed above the surface of the bone, it may be very difficult to find later when metal removal is required. Another alternative is to leave the end of the wire longer and just under the skin to facilitate removal. Pressure on the skin from within (and possibly from without due to dressings or plaster casts) may produce skin necrosis and infection around the wire tip. It is therefore recommended that either the wires be left buried with a bent end to facilitate removal, or the tip of the wire be left protruding by a centimeter or so from the skin. Prevent tension on the skin around the wire and protect it from unwanted blows. Either cap the wire with a commercially available wire cap or bend the end of the wire over. The former is preferable as it prevents catching the end of the wire on clothing. Reaction of the skin around the thin wire is minimal and infection unusual as long as it is stable in the bone. Subsequent removal of the pin is almost always easy and relatively pain free. In situations where K-wires are used in a tension band construct and functional postoperative therapy will be instituted, bend the ends of the wires into a U shape and impact them into the bone.

The special use of tensioned wires used in ring fixation and distraction techniques is described in Chapter 32.

**STEINMANN PINS**

**MATERIAL FEATURES**

In 1911, Fritz Steinmann (1870–1933), a surgeon in Bern, Switzerland, introduced pins that were thicker than those of Kirschner but otherwise very similar.

Steinmann pins are made in diameters of 3 to 6 mm and in lengths of 150 to 300 mm. The pointed end is usually of the trocar or diamond-pointed design (Fig. 11.3), but cove points are also available (Fig. 11.8). The cove point has a positive rake angle, which cuts bone rather than scraping it as occurs with the trocar and diamond tips. Flutes facilitate removal of chips from the hole made in the bone. Heat generation when using the cove point is probably less than with the trocar or diamond-tip Steinmann pin. In general, however, predrilling with the appropriate drill bit is recommended before pin placement into cortical bone. Predrilling is usually not necessary in cancellous bone.

![Figure 11.8. The cove point of a Steinmann pin.](http://gateway.ut.ovid.com/gw2/ovidweb.cgi)
Steinmann pins can be smooth or threaded. The threading of the pin facilitates fixation within the bone so that infection, which is facilitated by metal–bone motion, is prevented. Steinmann pins that are threaded only in the central region are easier to introduce and are as effective as fully threaded pins (Fig. 11.9). The thread diameter is 0.5 mm larger than the pin, so that the threaded segment is no weaker than the remainder of the pin.

**INDICATIONS FOR USE**

Steinmann pins are used mainly for traction through the femur, the tibia (proximal or distal end), or the os calcis. Traction is best applied with the use of a Böhler stirrup or bow, which fits over the ends of the pin. The design of the clamps holding the pin is such that movement of the stirrup does not rotate the Steinmann pin and cause it to loosen, because the bearings on the stirrup clamps allow free rotary movement on the pin (Fig. 11.10).
Chapter 10 for technical details.

**PINS INCORPORATED IN CASTS**

The incorporation of one or two transverse Steinmann pins into each end of a long bone fracture and then, after reduction, incorporation of the pins into a cast (i.e., "pins-and-plaster" technique) was used for many years. The stability of this construct is not very satisfactory, however. There is always a tendency for the plaster cast to loosen and, by its weight transmitted to the pins, provoke pin loosening and pin tract reactions (see Chapter 10). The use of pins-and-plaster techniques has largely been replaced by the more efficient and advantageous external skeletal fixators, which are discussed later in this chapter and in the various sections on fractures.

**TECHNIQUE OF PIN INTRODUCTION**

Steinmann pins can be introduced with a Jacob's chuck and T-handle or hand drill into soft bone, but this technique tends to lead to inaccurate pin placement. Particularly in hard cortical bone, such as the upper end of the tibia in young people, free-hand introduction of a Steinmann pin is very difficult and inaccurate; in this situation, always predrill the pin tract with a drill bit having a cutting tip that does not generate heat. The use of a power drill to insert the Steinmann pin directly into dense bone may generate sufficient heat to cause bone necrosis; infection frequently ensues with loss of fixation and development of a ring sequestrum and osteomyelitis.

Similar considerations for the introduction of Schanz pins, which are partially threaded at their pointed tips and are used in the external fixation of bones, are discussed later in this chapter.

- Make an initial skin stab incision with its long axis in the line of subsequent traction pull.
- Use a soft-tissue guide over the appropriate drill bit and drill a pin tract at right angles to the subsequent traction pull.

- Then introduce the Steinmann pin by hand into the bone with a Jacobs chuck and T-handle, making the skin incision at the exit site of the pin tip. Little heat is generated with a sharp drill, so bone necrosis does not occur; infection, loosening, and sequestrum formation are much less likely, and greater accuracy of pin placement is achieved.

- Apply a Böhler traction bow or stirrup to the pin and apply traction.

- Release any skin compression developed on applying the traction by incising the skin next to the pin; this is necessary to prevent skin necrosis and subsequent infection. Keeping a snug fit of the skin on the pin in the absence of tension on the skin minimizes motion of the skin on the pin and helps to prevent infection, so close any excessive incision. Keep the pin sites dressed in a sterile fashion and cap the pointed tip of the Steinmann pin to prevent injuries.

**TENSION BAND WIRES**

**PRINCIPLES OF USE**

In regions such as the olecranon and patella, an understanding of active and passive muscle forces allows the use of a minimal amount of fixation material to obtain excellent fracture stability and immediate functional movements of the contiguous joints. The principle of the tension band wire is that tensile fracture distracting forces, which the wire can easily absorb, are converted into stabilizing compression forces passing through the bone. It is essential that the cortex distant from the tension band side be strong enough to bear the applied compressive load. Loss of bone stock or poor bone quality will allow development of bending stresses, leading to wire fatigue and failure of the fixation. Tightening of the tension band wire produces static compression, particularly through the cortex under the wire. On active joint flexion, dynamic compression results across the whole of the fracture surface.

The wire used for this technique should have considerable ductility, combined with a high yield point and ultimate tensile strength. The wire is usually available in diameters from 0.4 to 1.5 mm made from type 316 stainless steel or Vitallium. The modulus of elasticity of Vitallium is higher than that of steel and for the same strain should support higher loads than stainless steel of equal diameter. Wire is weakened by cold working (e.g., kinking, bending, twisting), so care must be taken to avoid damage during implantation.

**TECHNIQUE OF APPLICATION**

The tension band method can occasionally be used with wire alone, as in a transverse fracture of the patella in which an irregular fracture line allows perfect reduction by interdigitation of the fracture surfaces (Fig. 11.11). In most situations, however, axial rotational stability cannot be obtained without the addition of two parallel, longitudinally placed K-wires (Fig. 11.12). In comminuted fractures, the K-wires also assist in providing
some interfragmentary stability, which is completed by the tension band wire. The K-wires must be inserted in a parallel fashion. Crossed wires provide much less rotational stability and interfere with interfragmental compression. The K-wires also provide anchorage points around which the tension band wire can be placed.

Figure 11.11. Transverse patellar fracture stabilized by two tension band wires.

Figure 11.12. Transverse patellar fracture stabilized with two parallel, longitudinally placed K-wires and tension band wire.

Tension band wiring of a fractured olecranon is described to illustrate the principles of the technique (Fig. 11.13).

Figure 11.13. Transverse olecranon fracture stabilized with two parallel, longitudinally placed K-wires and a figure-eight tension band wire.
After exposure of the fracture, place a 2 mm drill hole 2–3 cm distal to the fracture in a transverse fashion, passing just ventral to the dorsal cortex (Fig. 11.13). Then pass a 1.0 mm (18-gauge) or a 1.2 mm (16-gauge) diameter wire through the hole and displace the wire distally out of the proximal fracture field.

To control fragment rotation, insert two 1.6 mm diameter K-wires parallel from the tip of the olecranon into the distal fragment (Fig. 11.13). This can be achieved using a 2 mm triple guide, or the wires can be inserted retrograde from the fracture site to exit the tip of the olecranon.

After fracture reduction, advance the 2 K-wires 3 or 4 cm into the distal fragment. Alternatively, the wires can be inserted in an antegrade manner from the tip of the olecranon before fracture reduction, allowing their accurate placement within the medullary canal to be confirmed before reduction and driving of the wires across the fracture site. With more experience, after anatomic reduction of the fracture, the K-wires can be inserted from the tip of the olecranon across the fracture site and into the distal fragment. More secure fixation is obtained by drilling the wires through the anterior cortex rather than placing them in the medullary canal.

Place the ductile wire around the protruding proximal tips of the K-wires in a figure-eight fashion. Be certain that they are against bone. Throw a simple loop in the midpoint of one limb of the figure eight, and complete the opposite limb by twisting the two ends of the wire (Fig. 11.13). Twisting the loop and two ends of the wire alternately allows well-controlled and equal tension in the whole figure-eight wire. Achieve wire tightening with bullet-nosed pliers, being careful that the wire ends are
arranged in a helical fashion one around the other and that the pliers do not score
the tensed wire. Shorten the twisted wire ends and the twisted loop to about three
helical twists, and bend the wire ends away from the subcutaneous region to lie
alongside the bone. Bend the proximal protruding K-wires twice, shorten them
appropriately, and then impact them, like a staple, into the bony tip of the olecranon
(Fig. 11.13); this prevents migration of the pins. Even with some comminution of the
olecranon, the tension band wire technique can still be used after reduction and
fixation of the minor fracture fragments with lag screws; thus, excision of the
olecranon can usually be avoided.

- Commence immediate postoperative active flexion exercises for the elbow; extension
exercises should proceed with more care because the bone–fixation complex is less
stable in extension. If the proximal ends of the K-wires are not sufficiently impacted
into bone, they can back out and protrude under and even through the skin (68).
Another occasional complication is for the tension band wire to cut out of the distal
fragment if it has not been inserted deeply enough below the dorsal cortical surface.
After fracture union, the tension band wires tend to be uncomfortable. Removal is
often necessary. The tension band wiring technique can similarly be employed for
transverse and comminuted patellar fractures, fractures of the femoral greater
trochanter, fractures of the malleoli (particularly where small or osteoporotic
fragments are involved), and fractures of the distal end of the clavicle (Fig. 11.12
and Fig. 11.14).

Figure 11.14. Tension band wiring techniques
employed to stabilize greater trochanteric,
comminuted medial malleolar, and distal clavicular
fractures.
CERCLAGE WIRING

PRINCIPLES OF USE

Cerclage wiring techniques have some utility for provisional fixation of long-bone fractures or for definitive fixation, usually in combination with other fixation devices.

The wire applicable for cerclage is of the same type as that described for use in tension band wiring. Wire diameters of 0.8 to 1.25 mm are commonly used, and the strength varies directly with the square of the diameter. Two wires may be twisted to form a double strand, which may have greater flexibility than a single wire and is less likely to slip on the bone. Some cerclage wires are manufactured with a loop in one end, so that after passage around the bone the other end can be threaded through the loop and kinked backward to quickly achieve temporary fixation (Fig. 11.15). Regular wire can be tightened around the bone by twisting the two ends one around the other in a helical fashion with the aid of bullet-nosed pliers or one of the many available wire tighteners, while maintaining adequate tension on the wire (Fig. 11.15). A minimum of two full twists is necessary for maximum strength with 1.0 or 1.2 mm diameter wire, and the pitch of the twists should be as high as possible (50).

Any method of securing the wire ends that is stronger than the yield strength of the wire is satisfactory. For definitive cerclage wiring, it has been suggested that tying a formal square knot between the wire ends produces a fixation least likely to disengage (50). After the first throw of the knot and subsequent tightening, however, it is very difficult to maintain wire tension during the second throw of the knot (47,86). Although it is unlikely to completely unfold, with time the knot will commonly relax and precipitate failure of fixation. Knots therefore are suitable only for wire securing soft tissues. Helical twisting of the wire ends is easily applied, maintains the initial fixation tension, and will untwist only at tension loads beyond an acceptable limit. Anchoring the twisted wire tips by folding them down into a predrilled hole has been shown to produce the least slippage compared with other methods (48). The AO loop with bending of the free end under the wire also produces a satisfactory fixation strength, but the passing of the free end of the wire between bone and the tightly

Figure 11.15. Methods of joining ends of wire. A: One end of the wire is passed through a loop in the other end and kinked backward for temporary fixation. B: Helical twisting at a high pitch at the ends of the wire for temporary or definitive fixation. C: Technique like (A) but with one end of the wire passed under itself and against the underlying bone.
opposed cerclage can be very difficult (Fig. 11.15) (50,111).

Wire of insufficient strength can fail during clinical use by yielding, elongating, or fatiguing due to repetitive loading. This is especially true if the wire has in any way been scored before or during application (29).

Permanent cerclage wire fixation has sometimes been condemned as interfering with the periosteal circulation and thus producing bone necrosis. However, it has clearly been shown that the bone cortex receives most of its vascular supply in a centrifugal fashion from the medullary cavity, and even complete loss of periosteal blood supply may not lead to cortical necrosis. The periosteal vessels also tend to pass vertically into the cortex and not run along the cortical surface. Therefore, thin cerclage wires placed circumferentially at intervals are unlikely to severely damage periosteal blood supply in mature or immature bone (46,85,112). This contrasts with previously used wide Parham bands, which did eliminate periosteal blood supply from relatively wide segments of underlying bone (77,85). Recent modifications of Parham bands, as described by Partridge, are made of nylon and have elevations on the underside of the band that prevent wide contact and constriction on the bone by the band (78). This modified form of cerclage fixation may be useful in situations in which severely osteoporotic bone prevents other forms of stable internal fixation.

The method, however, has been condemned when used to control butterfly fragments in femoral shaft fractures, in which erosion of the bands into the cortical bone has sometimes been found (54).

The use of cerclage wire placed like a purse string circumferentially around the bone in the treatment of patellar fractures is now considered obsolete. This technique is not efficient and permits fracture fragment separation and mobility (108). Tension band wiring techniques described in this chapter are much more applicable to the problem.

TEMPORARY WIRING

During fixation of diaphyseal fractures in which a butterfly fragment is diametrically opposite the line of approach to the bone, the judicious application of a temporary cerclage wire may hold the butterfly fragment reduced so that lag screws may be inserted into it (Fig. 11.16). After stable screw fixation, remove the cerclage wire.

*Figure 11.16. Temporary cerclage wiring to facilitate lag screw fixation.*
Temporary cerclage wires may also be used prophylactically around the femur to prevent splitting during press-fit insertion of an uncemented femoral prosthesis.

**DEFINITIVE WIRING**

The use of cerclage wires inserted through small incisions to treat oblique or spiral diaphyseal fractures appears at first to be attractive (24,86). Even if stable fixation is initially obtained, however, the likelihood of the development of fracture angulation and loss of stability is significant because of the inevitable loading of the bone. Supplementation with some form of external casting is required, and this obviates early functional treatment of the limb. Stable closed intramedullary nailing of a diaphyseal fracture usually solves the problem more efficiently than cerclage wiring alone. However, several cerclage wires may be used in a supplementary fashion at 1 cm intervals along the shaft with intramedullary nailing (Fig. 11.17) or Ender rodding and as an adjunct to the Zickel nail in subtrochanteric fractures (53,73,118).

**Figure 11.17.** A: AP radiograph of femoral fracture with one large, free fragment. B: AP radiograph of femoral fracture treated with intramedullary nailing and three cerclage wires.
- Pass the wires at $90^\circ$ to the long axis of the bone so as not to slip longitudinally and loosen. All cerclage wires around the bone should be placed under the same tension to distribute the subsequent strain evenly between the wires; a wire tightener whose tension can be calibrated is necessary.

- Use a wire passer to facilitate passage of the wire around the bone and minimize soft-tissue trauma.

- Obtain anatomic reduction of the fracture before wire tightening; otherwise, wire loosening in the postoperative period is likely as settling of fracture fragments occurs. Cerclage wiring techniques may also be used in the proximal femur where a fracture has occurred during or after the insertion of a femoral prosthesis. Cerclage wiring can be very effective in this situation if care is taken to slightly notch the bone to prevent the wire from sliding distally along the taper of the femur.

**CABLES**

Dall and Miles (34) have developed a cerclage system employing two different sizes of cable that can be crimped to a grappling device. Similar devices are available from most orthopaedic implant companies. The mechanical properties of the multifilament cable are superior to monofilament wire in resistance to fatigue, and the cable has a higher yielding and breaking strength. The cable is also easy to work with because it does not have a tendency to kink. The cable-grip system was originally developed to facilitate reattachment of the greater trochanter in total.
joint arthroplasty, but it has proven to have many applications in internal fixation (34).

C. PRINCIPLES OF EXTERNAL FIXATION

Since their first application in 1853, the indications, popularity, and designs of external fixators have changed continuously. A variety of reliable pin fixators are now available with different clinical and mechanical properties (13). Ring fixators have become accepted tools for correcting limb-length discrepancies and malalignments, compensating for bone loss, and correcting soft-tissue contractures (72). Additional indications for ring fixators include severely comminuted peri- or intraarticular fractures, particularly in osteopenic patients. Recent efforts to make external fixators safer and more effective have made them invaluable tools in the care of injured and deformed patients. The devices are as reliable as plaster casts and internal fixation, yet more versatile, and they encompass a wider range of indications (13,14,37). External fixators are most useful when other methods of skeletal fixation seem too risky or when temporary fixation is required until tenuous soft-tissue conditions have resolved and definitive internal fixation is safer.

Although the general principles of use are very similar for pin and ring fixators, this chapter focuses on pin fixators that predominate in the treatment of acute, traumatic, and infective conditions. See Chapter 32 for a thorough discussion of ring fixators. Comminuted juxtaarticular fractures, particularly in the proximal and distal tibia and distal femur, are now frequently managed with hybrid external fixators, putting to best use the advantages of a ring fixator adjacent to the joint and a unilateral half-pin fixator on the diaphysis.

TERMINOLOGY AND COMPONENTS

Although the many different pin fixator designs can be confusing, closer analysis shows that each device comes with a limited number of similar components. These can be assembled into four frame types with distinct clinical properties and mechanical features (9,13).

FIXATION PINS

Half-pins are available with threads of various lengths on one end and rounded or sharp tips. I prefer self-cutting and self-tapping pins (Fig. 11.18) as they are simple to use. Various diameters and lengths are available, from the smallest for the digits up to the largest for the femur and pelvis.

Figure 11.18. A: Pins. a, Half-pins; b, centrally threaded transfixion pins. B: Connecting elements. a, Simple rod; b, rod with compression and distraction capabilities; c, rod with terminal universal articulations and capability for compression, distraction, and free axial sliding; d, circular connecting element. C: Articulations. a, Simple, adjustable clamp; b, universal clamp.
Full or transfixion pin designs with a threaded central portion provide good bone fixation without irritating the skin.

Connecting rods or ring elements connect the pins in the same or in different bony fragments. Complex rods have in addition a built-in capability to compress or distract, provide axial loading across the fracture at specific loads and excursions, and provide articulations for angular adjustments.

Simple articulation components connect two isolated pins, two rods, or a pin and a rod. Modular articulations hold two or more pins in one clamp, which is connected by a universal joint to a longitudinal rod.

Instrumentation usually includes wrenches, some with quantitative torque-measuring capabilities, to tighten the articulations; hand-held devices to insert and remove pins; drill bits; drill guides; depth gauges; pin caps; removable compression devices; and pin cutters.

**FIXATOR FRAMES**

The three-dimensional structure that is built with the components of a device is called a fixator frame or fixation configuration. In accordance with a frame’s space requirements, we differentiate between unilateral and bilateral frames (11) and multiplanar devices. Each of the former two frame types can be applied in a one- or two-plane configuration. One-plane configurations are less cumbersome, and two-plane configurations are more effective in neutralizing bending and torsional moments (Fig. 11.19).

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*Figure 11.19. The four basic configurations of external fixation frames. (From Behrens F, Searls K. External Fixation of the Tibia: Basic Concepts and Prospective Evaluation. *J Bone Joint Surg Br* 1985;68:246, with permission.)*
One-plane unilateral or half-frames are versatile (11,14,37). In the past, however, they were afflicted by a high rate of pin tract infections, malunions, nonunions, and component failures (25,96,105). Weight bearing was often possible only after advanced consolidation of the fracture callus. Most of the mechanical disadvantages of these configurations have been resolved through the introduction of stiffer components or a combination of stiffer components and mechanical optimization of frame designs (10,37,41). Two-plane unilateral frames (e.g., Delta frame, tent frame, triangular frame) can provide increased frame stiffness even with the use of relatively weak components, but they are more cumbersome and may interfere with wound access and secondary operative procedures (9,11).

One-plane bilateral configurations (e.g., quadrilateral frame, bilateral frame) were frequently used during the 1970s, when it was felt that the transfixion pins and the bilateral longitudinal support system would render them considerably stiffer than the traditional unilateral designs (56,105). Subsequent mechanical studies showed that these frames are rather weak in resisting sagittal bending moments (12,19). The insertion of multiple closely spaced transfixion pins caused compartment syndromes, neurovascular injuries, and
impairment of musculotendinous units with resulting joint stiffness (11). One-plane bilateral frames are therefore considered unsafe in most locations and have been largely abandoned. The stiffest configurations, two-frame bilateral frames, have been advocated for the management of infected and unstable fractures, in particular pylon fractures of the ankle, or to provide optimal conditions for bone healing. Although mechanically better balanced than one-plane bilateral frames, they are not commonly used today; new unilateral fixators work as well and are not afflicted with all the disadvantages and complications caused by transfixion pins and bilateral rods.

**BASIC CONCEPTS**

To be safe and effective, the application of a fixator frame must avoid iatrogenic injuries (11,14,48). The frame must minimize obstruction to other operative procedures, be adaptable to a wide variety of injury patterns, and be stiff enough to maintain alignment under various loading conditions. Its use should facilitate full weight bearing yet produce a low rate of serious complications. These goals are best achieved by adhering to three basic principles (9,11,14). In decreasing order of importance, these principles demand that an applied frame minimize the risk of injury to the vital limb anatomy, provide ready access for wound debridement and secondary procedures, and meet the mechanical demands of the patient and the injury.

**LIMB ANATOMY**

The shape and size of the soft-tissue corridor through which pins can be safely inserted is primarily determined by the location of the main vessels, nerves, and musculotendinous units. Of the two limb segments that make up the lower extremity, the distal segment is much better suited for the application of an external fixator, because the principal bone lies eccentrically and the pins can be inserted through a subcutaneous bony corridor (14,42).

Sequential cross sections of the lower leg (Fig. 11.20) show that in the proximal third of the tibia, pin placement is safe within an arc of 220°, which extends from the posteromedial border of the tibial plateau to the proximal tibiofibular joint (42). Excluded is a small rectangular area overlying the patellar tendon. This safe anteromedial corridor decreases to 140° just below the tibial tubercle and to 120° at the ankle joint. Therefore, half-pins are safest distal to the tibial tubercle. Full transverse pins tie down the muscles of the anterior compartment; in certain locations neurovascular structures are threatened by injury from a pin, so their use should be minimized and their insertion should be done judiciously.

![Figure 11.20. The “safe corridor” for pin insertion in the lower leg. A: Proximal to the tibial tubercle, pins can be safely inserted within an arc of 220°. B: Just below the tibial tubercle, the safe arc decreases to 140°. C: In the distal third of the leg, the safe arc remains 140°, but the anterior tibial vessels and deep peroneal nerves become vulnerable as they cross the lateral tibial cortex. D: Above the ankle joint, the safe arc is 120°. E,F: Pins in the tarsal or metatarsal bones may be used to splint the ankle joint if neurologic or soft-tissue injuries prevent the application.](http://gateway.ut.ovid.com/gw2/ovidweb.cgi)
Two potentially dangerous pin exit areas deserve special attention. Proximally, a pin can pierce the protective posterior muscle layer and injure the posterior neurovascular structures. This is prevented if the pin exit area is limited to the medial third of the posterior tibial cortex. In the distal third, the anterior tibial vessels are vulnerable along the lateral tibial cortex, which therefore should be avoided. Whenever possible, pin placement should be limited to areas where the tibia lies subcutaneously.

In the proximal segment of the lower extremity, the femur is circumferentially covered with soft tissues. There is no ideal corridor available as all pins pierce the thigh musculature before they are seated in the bone (3). Preferred pin placement is from the lateral side, just anterior to the intermuscular septum. Half-pins are essential because they transfix only the vastus lateralis. Sometimes the pins can be inserted anterior to the lateral intermuscular septum and posterior to the vastus lateralis, but they still limit the excursion of the iliotibial band and thus restrict knee motion while the fixator is in place (3,9). Medial-pin exit sites that are between the midfemur and the distal fifth are in a danger zone, because in this region the superficial femoral vessels and the saphenous nerve are tightly held in the adductor canal and are vulnerable to pin injury. If pins in these locations are essential, place them using open technique and avoiding the neurovascular bundles. These same considerations apply to the upper extremity. Only the subcutaneous borders of the long bones are reasonably safe, but even there tendons and cutaneous nerves are still at risk of injury. In general, place upper-extremity fixation pins with open technique.

The regional anatomy in the lower leg limits the choice of safe frame types to one- or two-plane unilateral configurations. Within the safe soft-tissue corridor, the best pin location, frame geometry, and frame placement are determined by the size and severity of soft-tissue lesions, and by the comminution and stability of the bone injury. Adapt each frame to the injury at hand to permit the best possible wound access for initial care, repeated debridements, and secondary soft-tissue procedures such as the transfer of local and distant soft-tissue flaps and the placement of bone grafts. Within the safe corridor, place...
pins and frames away from the injured area and the principal access routes. If an injury involves mainly the medial side of the leg, apply the frame anteriorly or anterolaterally; a lateral injury may call for a medial or anteromedial frame (Fig. 11.21).

**Figure 11.21.** A gunshot wound involving the lateral aspect of the proximal tibia with severe loss of soft tissue and bone. A: Initial appearance from the lateral side. B: Stabilization by an external fixator placed on the medial side. C: The soft-tissue defect covered by a lateral gastrocnemius flap; there is no interference from the fixator frame. A split-skin graft was used to cover the muscle flap. D: Radiographs at this stage. E: Elevation of the healed gastrocnemius flap to allow the skeletal defect to be bone grafted. F: At 5 months, the fracture has healed, and the patient has borne full weight for 4 weeks. G: Radiographs 1 year after the injury. (From Behrens F, Sears K. External Fixation of the Tibia: Basic Concepts and Prospective Evaluation. *J Bone Joint Surg Br* 1985;68:246, with permission.)

### MECHANICAL DEMANDS

To be mechanically effective, the stiffness of a fixator frame should control the prevailing forces and moments at the fracture site. Information based on the size and weight of the principal lower extremity segments and the distribution of the muscles surrounding the femur and tibia indicate that, in the supine position, sagittal bending moments are two to five times larger than the moments acting in the frontal plane. After a patient is weight bearing, compressive loads and torsional moments around the longitudinal axis gain in importance (11). However, there is little change in the ratio of anteroposterior-to-frontal bending moments. This suggests that regardless of other mechanical properties, a fixator frame in the lower extremity should be about two to five times stiffer in the sagittal than in the frontal plane (12). For tibial fixators, this stiffness ratio is most easily achieved if the principal pin plane is oriented in an anteroposterior (AP) direction. Although clinically appropriate, lateral femoral frames are not ideal mechanically because they are relatively inefficient in resisting fragment motion in the sagittal plane. To counteract this tendency, spread the pins in each principal bony fragment as far apart as possible. Use stiff longitudinal rods and double-stack them if necessary (3).

The size of the fixator components and the frame geometry are other factors that influence the application of a mechanically effective frame. Assuming that stainless steel components are used, the pins should have a diameter of at least 5 mm, and the longitudinal rods should have a diameter of 8 mm or more. The articulations must not slip within the range of clinically applied torques. Experimental work has shown that the following methods increase frame stiffness in one or more loading modes (10,12):

- Increasing the pin spread within each main bony fragment (14)
• Reducing the distance between the bone and the longitudinal rods (13)
• Attaching a second longitudinal rod to the same pin plane (10)
• Erecting a second half-frame at an angle to the first (i.e., creating a two-plane unilateral frame)

These mechanical measures alone or in combination can accommodate most tibial and femoral injury patterns without the need for bilateral frames. Unilateral frames suffice for most upper-extremity injuries.

**PREOPERATIVE CONSIDERATIONS**

The successful and effective use of external fixation devices rests on thorough preoperative planning (14). Although much of this planning process occurs before the fixator is applied, it must anticipate the most likely time course of healing and the principal variations and potential complications that might be encountered.

In the initial assessment, note the patient's age, size, premorbid condition, socioeconomic circumstances, and the cause, severity, and extent of the injuries. Determine whether external fixation is the best method for treating the patient's injuries, what is the best device and in what configuration, whether the fixator will be used alone or in conjunction with internal fixation (Fig. 11.22), what equipment is available, and what surgical skills are needed. Determine also if the full frame should be applied immediately or completed at a later time, and whether the fixator will remain in place until the fracture is healed or will be replaced with a cast or internal fixation as soon as the soft-tissue conditions permit (14).

If there is a choice of several devices, the sturdier designs are preferred for patients who are heavy or who have an unstable fracture pattern. For the younger child, a wrist or upper extremity device may be sufficient. When rapid application is essential or proper radiographic control unavailable, fixators with full universal joints at both ends are ideal, because they facilitate alignment and length adjustments at a later time (88,96).
When dealing with complex fracture patterns that require repeated assessment of healing, devices composed of radiolucent carbon fiber components are advantageous.

**CONFIGURATIONS**

The factors that determine location and configuration of a particular fixator frame depend on the extent of the soft-tissue injury within the safe corridor, the stability and location of the fracture, the size of the patient, the presence of associated lesions, the size of the fixator components, and the designs of the fixator articulations (14).

When using simple fixators that allow for free pin spread and provide moderately stiff components, 80% to 90% of the applied frames are of a one-plane unilateral design (13). For devices that provide universal articulations but lack the mechanical advantage of maximal pin spread (e.g., Hoffmann apparatus, Orthofix), the risk of slippage at the articulations is considerable. With these fixators, take care to use undamaged functioning articulations and possibly double-stacked one- or two-plane unilateral frames (96). These configurations are preferred for fractures with segmental bone loss or extensive comminution (Fig. 11.23, item 2, lower drawing). One-plane frames with double rods (Fig. 11.19, upper drawing) have a rigidity pattern similar to that of two-plane unilateral frames, but they are less cumbersome and allow better wound access (10). Due to their greater rotational rigidity, two-plane unilateral frames may be still preferable for the management of infected nonunions and lesions that are accompanied by substantial bone loss.

**Figure 11.23.** The recommended configuration of fixator frames for different bone and soft-tissue injuries. The location and extent of the lesion is indicated, on the left, by the crosshatched area. The preferred frame is shown, with solid bars representing the pins; on the right are the indications for the use of the configuration. (From Behrens F, Searls K. External Fixation of the Tibia: Basic Concepts and Prospective Evaluation. J Bone Joint Surg Br 1985;68:246, with permission.)

One-plane unilateral frames are ineffective in stabilizing comminuted proximal and distal periarticular fractures, which often provide only short metaphyseal or epiphyseal fragments for pin insertion. With simple frame modifications (Fig. 11.21B; Fig. 11.23, items 3 and 4), however, these fractures are easily managed. Proximally, where the safe corridor opens wide, subchondral pin placement affords anchorage for two or more half or full pins (Fig. 11.23 items 3 and 4).
Over two or more longitudinal rods, these pins are then rigidly connected to several distal pins, which in the tibia are placed close to the sagittal plane. After the application of these frames, the knee is moved through a full range of motion to ensure free mobility of joint capsule, pes anserinus, and iliobibial band. Distal tibial fragments as short as 2 or 3 cm long can be stabilized by inserting two or more pins on either side of a longitudinal rod (Fig. 11.23, item 4). For the immobilization of distal intraarticular fractures, a talar or calcaneal pin is connected with two rods to two or more anterior half-pins in the proximal tibia (Fig. 11.23, item 5). Hybrid frames work well and to some extent have replaced these frames. These are presented in more detail in Chapter 23 and Chapter 25.

**COMBINED INTERNAL AND EXTERNAL FIXATION**

Additional internal fixation is occasionally employed in the management of type II or IIIA open tibial fractures with two or three comminuted fragments. After anatomic reduction and interfragmental compression with screws, a relatively rigid external frame is applied instead of a neutralization plate. This approach has been quite successful in metaphyseal fractures, which generally heal within 2 to 3 months. In the diaphysis, however, high complication rates, mainly in the form of refractures, have been common. This is not surprising, because in cases of avascular diaphyseal fragments bony union is often delayed for more than a year. Additional detail on this issue is provided in Chapter 24.

**SURGICAL TECHNIQUES**

- Drape the limb to keep the injury zone and the adjacent joints accessible in the operating field. Avoid adhesive plastic drapes where pins will be inserted, as they tend to wind up on drill points and pins and may be inadvertently transported deep into the wound. An image intensifier helps to assess proper pin location, pin depth, and fragment alignment, and it is particularly valuable in dealing with closed...
fractures that do not allow direct manipulation of the fracture fragments.

**PIN INSERTION**

- Make a skin incision just large enough to accommodate the drill point and pin sleeves to be used. Most manufacturers provide matched protective sleeves for drilling, depth measurement, and pin placement.

- In deeper bones, incise the deep fascia (a small x often facilitates guide sleeve placement); separate muscle fibers with a Metzenbaum scissors or a small elevator and elevate the periosteum at the pin site. Many half-pins are now available with specially designed tips that are self-cutting and self-tapping and have flutes to deliver bone fragments. To avoid overheating, bone necrosis, and pin breakage, never insert these with power but rather with hand drills provided by the manufacturer.

The following technique applies to pins that require predrilling, which make up the majority of pins used today.

- Insert the protective sleeves down to the bone.

- Gently impact the teeth of the sleeve or trochar into the bone, if called for by the manufacturer.

- Drill the initial hole with the size called for by the manufacturer for the pin diameter to be used. Use power, cool the drill, and avoid overheating the bone.

- Usually one drill size suffices. In some cases, the near cortex must be drilled with a larger diameter to accommodate a larger smooth shank on the pin.

- Select the appropriate pin and the thread length: in some systems, a depth gauge is required, or the drill may be calibrated.

- Insert the pin until at least one full thread penetrates through the opposite cortex. Carefully monitor this with the fluoroscope, as in some systems the pin cannot be reversed without loosening.

- Many half-pin systems allow selection of a total thread length that is 5 mm less than the overall diameter of the bone at the site where the pin is inserted. This permits the wider nonthreaded shaft of the pin to fit tightly into the proximal drill hole and places a smooth shank at the level of skin. This reduces skin irritation and doubles the bending stiffness of the pin (Fig. 11.25).

*Figure 11.25. Seating of half-pins. A: Threaded pin portion protrudes beyond the skin. This tends to cause skin irritation and pin-tract infection. Pin*
Once the entire frame has been assembled and the fracture reduced, check the skin around each pin to be certain that tension on one side of the pin is not present. This is indicated by gathering of the skin. If there is tension, incise skin where it is gathered until it lies tensionless around the pin.

Differential motion of skin on the pin can result in bacterial contamination of deeper tissues; therefore, gently close any excessive incision about the pin with a fine nylon suture that can be removed when the skin is healed.

The sequence of subsequent pin insertion depends on the type of fixator used. Many frames allow independent pin insertion, in which case be certain that the limb or the fracture is aligned and insert the next pin most distant from the initial pin. The initial pin should have been the most extreme pin at the other end of the bone. Insert the second pin using either a template guide or the preassembled fixator as a guide.

In some frames, the pins are applied in clusters in the proximal and distal fragments. With these fixators, independent arrangement of the pins anywhere along a fixator bar, such as in the unilateral frame, is not possible as the pins are inserted through a clamp or ring that holds the cluster of pins in one fragment in a more-or-less fixed arrangement relative to the others. The exceptions are Ilizarov type ring fixators, where pins can be placed anywhere along the 360° arc of the ring, and pin clamps that allow a limited range of placing the pins longitudinally on the bone. With these fixators, maintenance of overall alignment of the limb is less crucial, as universal adjustment clamps permit reduction of the fracture after the fixator has been applied; however, each fixator has a limited range of adjustment. It is possible to apply pin clusters so out of alignment with each other that reduction cannot be achieved. Therefore, it is always prudent to maintain general overall alignment of the limb, particularly rotation, as any type of fixator is applied. The following steps describe the technique for a typical fixator of this type.

- Using the manufacturer's guide or the fixator itself, insert the pins in one fragment and then the other. A wide spread of the pins within the range allowed by the clamp increases stability. Always apply the two outer pins on a given clamp first, to be certain that all pins will be anchored in bone.

- Now reduce the fracture; with the universal joints loose, obtain anatomic reduction.
Tighten the universal joints or adjustments once reduction is achieved.

- If fracture-fragment alignment is not satisfactory on subsequent fluoroscopic examination or x-rays, loosen the universal joints and repeat the reduction maneuver.

**FRAME APPLICATION**

The design of the clamps largely determines the sequence of steps for the application of a fixator frame (9). With simple fixators, each pin is independently connected to the longitudinal rod in several steps as follows (3).

- Insert one pin into each main fragment, generally starting with the pins close to the joints (i.e., farthest from the fracture). Maintain gross alignment of the limb (14).
- Reduce the fracture. Apply adjustable clamps to each pin and connect them by a longitudinal rod. Then manually reduce the fragments and tighten the two clamps to achieve temporary reduction. Proper rotational alignment is crucial (13).
- Insert the remaining pins (10).
- Adjust the fixator. Adjustments in the plane of pin insertion are easily achieved by loosening the pins. For angular adjustments in another plane, replace the longitudinal rod by two shorter ones that are connected over a central universal joint. For the correction of significant rotational malalignment, all pins except one in each fragment must be exchanged.

**HINTS AND TRICKS**

Whenever possible, achieve an anatomic reduction. For simple transverse or interdigitating fractures, axial compression of the fracture site provides additional stability. When axial compression is attempted with unilateral frames, the fracture fragments have a tendency to angulate away from the longitudinal rods. It is advantageous to start with the fracture fragments angled toward the rod(s). With increasing compression, the fracture fragments tend to straighten into anatomic alignment.

Proper rotational alignment and length is ensured by comparing the injured to the opposite limb, if it is uninvolved; for assessment of alignment, however, obtain AP and lateral radiographs that include the joints above and below.

**POSTOPERATIVE CARE**

In the early postoperative period, elevate the injured extremity, for example in balanced suspension with the calf muscles supported with a sling (Fig. 11.26). Support the ankle
joint in 5° to 10° of dorsiflexion with a prefabricated splint. If the patient has sustained a severe soft-tissue injury (in particular, compartment syndrome requiring fasciotomy, or palsy or paresis of the common peroneal or posterior tibial nerves) or bony injury distal to the ankle joint, replace the ankle splint with a transtarsal pin (Fig. 11.20E) or two metatarsal pins that are connected to the external fixator frame (Fig. 11.20F).

Figure 11.26. The early postoperative management of an open tibial fracture. The limb is suspended, the calf is supported, and the ankle joint is splinted in 5° to 10° of dorsiflexion.

As soon as the leg wounds permit, begin twice-daily, passive, active-assisted, and active range of motion exercises of knee and ankle joints. Follow with isometric muscle strengthening exercises across both joints and mobilization with crutches or a walker. As soon as tolerated, encourage the patient to partially bear weight on the injured extremity, progressing to full weight bearing as the fracture consolidates, if the fracture type and external fixator permit. If this course is conscientiously followed, approximately 70% of all patients with tibial fractures can advance to full, unsupported weight bearing before the fixator is removed or replaced by a different method of immobilization. Weight bearing has little to do with pin tract infection or pin loosening. Patients with segmental bony defects must be limited to bearing with only the weight of the limb.

CARE OF THE PIN SITES AND FRAME

After the initial operative procedure and any subsequent debridements, or additional soft-tissue or bony reconstructive procedures, the limb will generally be encased in a bulky postoperative dressing, which precludes access to the pin sites. Because the patient returns often to the operating room for wound debridement and subsequent reconstruction, there is no necessity for pin care by the nursing staff on the ward. In fact, exposing an open fracture wound on the ward unnecessarily invites contamination with nosocomial organisms. When the wound has stabilized and repeat operations are no longer necessary or are infrequent, it is appropriate for the nursing staff to begin pin care, particularly since the patient must be educated in this important aspect of care of the external fixator in an outpatient setting. Unless the patient is hospitalized for a prolonged period of time and is nonambulatory, pin care in the hospital differs little from what I prefer to have patients do at home. There is little in the literature to prove that one pin-care regimen is superior to another (98). I have found the following program to be effective and simple for nursing staff
and patient. Using this regimen, I have had external fixator pins located in cortical bone in place as long as 1 year with no complications.

- In the hospital setting, because the soft tissues are still edematous, serum and hematoma oozes from the pin sites and dries as a crust around the pins. This can be a source of bacterial colonization and skin irritation. Once a day, the nursing staff should expose the entire external fixator and all of the pin sites, and wipe down the pins and frame.

- The dried exudate can be removed by any method that is gentle, comfortable for the patient, and effective. Cleaning with a 50% hydrogen peroxide solution, or simply washing the pin sites with sterile gauze and soapy water are equally effective. (Although many surgeons apply antibiotic or antiseptic ointment to the pin sites, I have not found these to be of any value, and this risks sensitizing the patient to the material used.)

- Dress the pin sites with a 2×2 or 4×4 gauze cut to fit snugly around the pin. (There are commercial sponges available for this purpose, but I have found these to be less effective than simple gauze bandages.) Wrap these into place to stabilize the skin and prevent vertical motion of the skin on the pin. This helps reduce bacterial contamination of the pin site caused by movement of the skin along the pin, and it makes the patient more comfortable. Once bulky dressings are no longer needed for the wound, these small gauze bandages can be held in place by plastic clips placed on wires or half-pins and slid down against the dressing to stabilize the skin. These were an innovation of Ilizarov and have proven to be very useful.

After discharge from the hospital, daily showers are simple for the patient and provide the easiest method for pin-site and frame care. As soon as the wound allows, have the patient take a daily shower, thoroughly scrubbing the external fixation frame and all of the pins and wires with ordinary soap and water (avoid strong soaps and those heavily perfumed) using a clean, fresh washcloth. Removal of tough crust is facilitated by a soft surgical brush and a child's toothbrush. After the shower, the patient should dry the apparatus and pin area with a freshly laundered towel different from the one used for the rest of the body, and dress the pin sites as described above. For the second pin-care episode each day, it is necessary only to clean the pin sites themselves using similar techniques.

Pin-site irritation or inflammation occurs at one time or another in most patients, but, if good technique is used, pin-tract infection should be uncommon (this is discussed below in the Pitfalls and Complications section).

Educate all patients about the mechanics of their frame, in particular how to keep the frame and pin clamps tight. If they are incapable of understanding, or of maintaining the frame, a relative or caregiver who will take this responsibility must be involved. Provide the patient with a wrench, or other appropriate tools, so that the components of the frame can be checked at least weekly to be certain that they remain tight.
Once the patient's condition has stabilized and it is evident that good care is being taken of the pin sites and frame, reliable patients may be able to go up to 6 weeks between follow-up visits. Less reliable patients may need to be seen by the surgeon weekly, and they may need frequent visits by a home health nurse to do pin-site and frame care.

**GETTING FRACTURES TO HEAL IN EXTERNAL FIXATION**

Many closed and open fractures treated with external fixation are of such severity that they will not heal readily without additional biologic or mechanical measures.

**SOFT-TISSUE COVERAGE**

Severe open fractures heal faster if they are covered with adequate soft tissue, in particular, muscle, which is a source of neovascularization (116). If coverage is not possible locally, free muscle or composite flaps should be placed early, because this tends to prevent the development of local wound colonization and subsequent osteomyelitis. This is a prerequisite for the success of later bone reconstructive procedures (88,105) (see Chapter 8 on soft-tissue management and Chapter 12 on open fractures for more detail).

**BONE GRAFTS**

Many adult patients with severe open tibial fractures need bone grafts to get the fracture to unite. When dealing with a Gustilo type IIIA or lower grade clean open wound that allows local closure after appropriate debridement, I may place an autogenous cancellous bone graft at the time of soft-tissue closure. After massive wound contamination, infection, or delayed closure with a flap, as in type IIIB or IIIC open fractures, wait until the soft tissues are fully recovered and there is no evidence of infection. This often requires 6 or more weeks. Reckling and Waters (83) place a cancellous or corticocancellous bone graft, often in conjunction with osteoperiosteal elevation through an anterior or medial incision. At the University of California, Davis, Trauma Center, we prefer the posterolateral approach applying a large cancellous autologous iliac graft, and we usually perform a tibiofibular synostosis (see Chapter 26 and Chapter 31).

**CHANGING FIXATOR STIFFNESS AND AXIAL MICROMOTION**

Many surgeons elect to replace the external fixator with a patellar tendon-bearing or long-leg cast as soon as soft-tissue coverage has been obtained (56,96). This is often successful in patients with stable fractures. However, unstable fractures and even stable fracture patterns often angle after fixator removal, even if immobilized in a long-leg cast. I prefer to hold these fractures in the external fixator until they are healed. After advancing the patient to full, unsupported weight bearing, gradually dismantle the more complex configurations (e.g., two-plane unilateral, one-plane unilateral with double rods) to one-plane configurations with a single anterior or anteromedial rod (Fig. 11.24). Then, sequentially loosen the pin clamps, starting with the pins closest to the fracture site, until the load is held only by the most proximal and most distal pins.

Another option is to loosen all the pins in the proximal or distal main fragment. This permits free axial loading while preserving angular and rotatory alignment (13). Although
attractive and logical, there is no proof that this approach leads to an increased rate of fracture healing. Easier to use are tube-type and other fixators that can be dynamized, some with very specific control over the excursion and amount of loading.

Early induction of axial micromovement at the fracture site has been shown to increase the rate of fracture healing (43,58). This is achieved with the help of a pneumatic actuator temporarily connected to the fixator. The actuator induces a loading regimen of 1 mm displacement at 0.5 Hz for 30 minutes each day. With this approach, a 20% reduction in the average healing time was achieved in a controlled trial of complex tibial fractures (59).

SECONDARY INTERNAL FIXATION

Delayed union or progressive malunion after a tibial fracture often is best handled by replacing the external fixator with an intramedullary rod or a plate. Internal fixation following removal of external fixator pins where infection has occurred, particularly osteomyelitis, is generally contraindicated until the infection has been eradicated. Although there is little information about results and complications after plating, indiscriminate secondary intramedullary nailing has been shown to have a high infection rate (70). However, secondary nailing can be performed with only a slightly increased infection rate if the procedure is carried out very early or within 4–6 weeks of fixator application (15). Even with these restricted indications, it is safest to place the limb in a cast for 2–4 weeks before proceeding with intramedullary nailing to allow the pin tracks to heal. Unless extraordinary circumstances prevail, avoid intramedullary nailing after local soft-tissue or bony infection or in a patient who once had a pin tract infection, because the sequelae of an infected medullary canal can be disastrous.

PITFALLS AND COMPLICATIONS

CHRONIC PAIN

Patients who experience more chronic pain than expected, particularly when associated with weight bearing or exercise, nearly always have a loose pin or wire. Once soft tissues have healed, the patient has recovered from the initial trauma and/or surgery, and the fracture site has begun to consolidate, the average patient should be quite comfortable in the fixator, requiring minimal across-the-counter pain medication. Pain is a greater problem when a vigorous rehabilitation program is in progress and the patient has pins through large soft-tissue envelopes such as in the thigh, where muscles, tendons, and fascia are constantly being tethered by or are moving on pins and wires. In these cases, careful monitoring of the rehabilitation program to minimize discomfort, and close cooperation among the patient, surgeon, and physical therapist, are essential.

In the vast majority of cases, however, pain is due to a loose pin. This is usually accompanied by evidence of pin-site irritation, discussed below. In the early stages, pin loosening can be difficult to detect. Most frequently, resorption of bone occurs in the near cortex, resulting in micromotion of the pin in this cortex, while the opposite cortex holding the tip of the pin remains solid. Early detection of this requires loosening the clamp...
attached to the pin and then careful palpation of the pin, wiggling it back and forth to detect this micromotion. Later, a radiolucent zone about the pin can be detected radiographically. This is a sure sign of pin loosening.

If the patient is midway in the course of fixator treatment, removal of the loose pin is necessary; it may be either left out or replaced with another pin in a sound location at least 15 mm or more from the original site. If the patient is nearing the end of treatment (e.g., the fixator needs to be left on for only an additional 1–2 weeks) and there is no evidence of infection, then shifting the pin clamp location on the fixator, slightly bending the pin to bring it against one cortex of its hole, will occasionally stabilize the pin and allow the patient to complete treatment. This is a temporizing measure that does not solve the underlying problem of pin loosening and should be used only in these special circumstances.

Pin loosening that results in pain is particularly a problem in ring and hybrid external fixators using tensioned wires in metaphyseal bone. Continuation of tensioned wire fixation where loosening of the wires has occurred guarantees persistent pain for the patient and eventually further pin complications of more severity. In the case of tensioned wires in metaphyseal bone, detection of loosening usually requires detaching the ring from the rest of the external fixator and manipulation of the ring to detect motion of the pin in the bone.

**PIN-SITE DRAINAGE AND INFECTION**

Pin-site problems manifest themselves as a progression of symptoms from slight pin-site tenderness, swelling, and erythema, to substantial serous exudate, to evidence of frank infection with purulent exudate at the pin site with or without evidence of abscess formation. If the patient has clinical evidence of infection and a radiolucent zone around the pin on a radiograph, then bone infection is usually present. In my experience, the most common cause of pin-site complications is loosening of the pin in the bone. In metaphyseal bone, this is most commonly the result of simple mechanical loosening due to the weak structure of the cancellous bone. In cortical bone, it is most commonly due to improper surgical technique producing necrosis of the bone as a result of overheating drill points or fixation pins. In the latter case, a remodeling response is precipitated in the bone immediately surrounding the pin, which rapidly leads to pin loosening and in some cases formation of a ring sequestrum around the pin, seen after pin removal when the central beam of the x-ray is directed along the axis of the pin hole. Management of pin-site irritation and infection is illustrated in Table 11.3. The pin must be removed, the soft tissues and bone thoroughly debrided, and appropriate antibiotics prescribed.

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**Table 11.3. Management of External Fixator Pin Site Problems**

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Note that oral antibiotics have only a small role to play in managing pin-site irritation. The typical situation in which a patient requires oral antibiotics occurs when the pins pass through a thick soft-tissue envelope, which, because of the patient's activities and rehabilitation, are moving on the pin, resulting in contamination and a low-grade cellulitis in the absence of any evidence of pin loosening or infection. This is most common in limb-lengthening and deformity-correction procedures where tensioned wire ring fixators or hybrid frames are being utilized. In these cases, I have found that a few patients do well on oral cephalosporins for 10 days or more if episodes of cellulitis occur. Always be alert for pin loosening and evidence of deeper infection.

Superficial cultures of pin tracts, regardless of clinical appearance, have no place in the management of pin-site complications. These cultures are nearly always positive, usually represent normal skin flora, and are of no help in prescribing appropriate treatment. I take cultures only when formal deep debridement of an infected or potentially infected pin site is carried out. These cultures are taken at the level of bone, preferably from a curetting of the pin tract.

DEFORMITY, DELAYED UNION, AND NONUNION

Progressive deformity in the fixator is usually caused by either pin loosening, loosening of components on the frame, or both. If deformity is noticed prior to consolidation of the fracture, then usually it is correctable by addressing pin or frame problems. Because of the nature of the fractures treated with external fixators, delayed union and nonunion are common and are best approached by manipulation of the frame or by bone grafting, as described previously. Conversion to some type of internal fixation is much less common unless done very early, as has been discussed. These issues are addressed in much more detail in chapters on each specific bone and on nonunions in this section of the book.

D. PRINCIPLES OF SCREW FIXATION

GENERAL PRINCIPLES

Screws can be used to attach implants such as plates and prosthetic devices to bone, to fix bone to bone, and to fix soft tissues such as ligaments and tendons to bone. Perhaps the most important use of screw fixation is interfragmentary compression, which improves the
mechanical stability of internal fixation by increasing the friction between bone fragments. This minimizes micromotion between the fragments by minimizing the effects of torsion, shear, and bending forces.

As described by Müller et al., interfragmentary compression can be static or dynamic (71). Interfragmentary compression with a lag screw is the best example of static compression. A screw functions as a lag screw when the threads obtain purchase only in the far cortex, and the thread of the screw or a nonthreaded portion of the screw passes freely through the cortex immediately beneath the screw head. Screws can be made to function as lag screws either by overdrilling the near cortex to prevent the threads from gripping, or by having smooth shanks in the portion adjacent to the screw head. Clearly, interfragmentary compression cannot occur if the screw threads cross the fracture site, unless compression is achieved by a bone-holding forceps at the time the screw threads cross the fracture. The screw then maintains, but does not itself exert, compression.

The holding power of a screw in bone is most dependent on the density and quality of the bone. Other factors related to the strength of screw fixation are the overall surface area of thread in contact with the bone and the configuration of the thread relative to the structure of the bone. Whether the hole is tapped or untapped influences the frictional force developed between the screw and the bone, and thus the tendency of the screw to back out. Because bone is either cortical or cancellous, and each type has very different structural characteristics, two types of specialized screws have been developed—cortical and cancellous (Fig. 11.27 and Fig. 11.28).

**Figure 11.27.** Cortical screws. Top: A 4.5 mm cortical screw with a core diameter of 3 mm, outside thread diameter of 4.5 mm, and thread pitch of 1.75 mm. Notice that the underside of the screw head is hemispherical in cross section. A 3.2 mm drill bit is used for the threaded hole and a 4.5 mm drill bit for the gliding hole. Center: A 3.5 mm cortical screw. In the AO system, two varieties of this screw are now available—one with threads like those on a machine screw, known as the 3.5 mm cortical screw, and the one here, the 3.5 mm cancellous screw. The screw illustrated has a core diameter of 1.9 mm, an outside diameter of 3.5 mm, and a thread pitch of 1.75 mm. A 2 mm drill bit is used for the threaded hole, and a 3.5 mm drill bit for the gliding hole. Bottom: The 2.7 mm cortical screw is used for fixation of small fragments, as in the hand and foot. The thread has a core diameter of 1.9 mm and an outside diameter of 2.7 mm. The threads have a 1 mm pitch. A 2 mm drill bit is used for the threaded hole and a 2.7 mm bit for the gliding hole. (From Müller ME, Allgöwer M, Schneider R, Willenegger H. *Manual of Internal Fixation*. New York: Springer-Verlag, 1979:33, with permission.)
CORTICAL SCREWS

Typical stainless-steel cortical screws used for large-fragment and small-fragment fixation are shown in Figure 11.27 (3).

These screws have spherical heads and are threaded for the full length of the shafts. A hexagonal screwdriver is used. Because there are no flutes on the tips of these screws, the bone must first be tapped to create threads for the screw. The advantage of tapping is that more engagement of the screw threads into bone is possible (Fig. 11.29). Because taps provide four cutting flutes, microfracture of the bone is less likely to occur. Theoretically, this produces better hold of the screw in bone. Disadvantages of tapping are that it requires an extra step in the operative procedure and, because a rather smooth track is established, the screw is more likely to loosen by backing out when it is subjected to cyclical stress.
Self-tapping screws using a four-flute tap-like cutting tip are also used. They are manufactured from a titanium alloy, and variations are available from several manufacturers (Fig. 11.30). These new screw designs surpass the holding power of non-self-tapping screws and are stronger due to their larger diameter and the use of titanium alloy. The major advantages are that the extra step of tapping is eliminated, and the screw is less likely to back out because of better frictional hold between the screw threads and bone. The only disadvantage is that 3–5 mm of screw tip must protrude from the bone to achieve maximum thread surface in contact with bone in the opposite cortex.

*CANCELLOUS SCREWS*

Compared with cortical screws, cancellous screws (Fig. 11.28 and Fig. 11.31) have larger threads with a higher pitch and usually a smaller core diameter, providing more surface area for purchase on bone. Because cancellous bone is fairly soft and easily deformed, tapping usually is not required. If the screw is inserted through cortical bone first, however, it is usually necessary to tap the cortex; for this reason, taps are provided for cancellous screws.
To obtain the best hold when placing a screw in cancellous bone, do not tap. As the screw penetrates, it compresses the bone to either side, thereby increasing the bone density in the immediate vicinity of the screw thread; this improves the holding power. Typically, cancellous screws have smooth shanks in the portion immediately adjacent to the screw head so that an automatic lag effect occurs without having to overdrill the near cortex. This is significant in the larger 6.5 mm screws, where a very large hole would need to be drilled in the near cortex to produce a lag effect. Varying thread lengths are available (16 and 32 mm). Fully threaded cancellous screws are available as well.

Today, many surgeons use cortical screws for internal fixation of the pelvis and fixation in the cancellous bone of juxtaarticular fractures such as those of the tibial plateau. These screws are inserted without tapping and take advantage of the compressive effect of the bone around the screw, as described above. Sometimes, a tap must be used to initiate penetration of the screw through the thin cortical cortex. If the opposite cortex is to be penetrated and it is more than one or two thread widths in diameter, pressure must be maintained against the screw to penetrate the cortex and to prevent stripping of the screw. This is the major disadvantage of this technique. The major advantage is that taps and the aggressive threads of cancellous screws do not need to be used in areas where excessive penetration of these sharp cutting surfaces may threaten neurovascular structures, and, in addition, a larger surface area of purchase of the screw threads on bone results in more holding power. This is a particularly good technique with self-tapping screws.

**SPECIAL FEATURES**

Most screws today have a spherical head that allows the screw to be angulated in all directions within a washer or plate while maintaining concentric contact between the screw and the side of the plate. The only disadvantage of the spherical head is that it is more prominent when used without a plate. This necessitates countersinking to avoid prominence of the head and to avoid the stress created by asymmetric contact of the underside of the head with the edge of the predrilled screw hole. Washers (Fig. 11.28) often must be used
with cancellous screws because the screw head tends to bury into the thin cortex overlying cancellous bone.

A specialized use for the spherical screw head (Fig. 11.32) is in achieving interfragmentary compression. The screw head is driven asymmetrically in the specially designed screw hole of the dynamic compression plate, which was pioneered by the AO Group (71). This design eliminates the need for an external compression device but has the disadvantage of limiting the angulation with which the screw can be driven. Extreme angulation of the screws may reverse the compression force to some extent. The amount of compression achievable is less than that possible with an outboard compression device, described below in the General Principles of Plate Fixation section.

**Figure 11.32.** Gliding-hole principle of the dynamic compression plate, in which the spherical underside of the screw glides down the incline plane of the screw hole in the plate. Interfragmental compression is achieved using a plate, without an external compression device. (From Müller ME, Allgöwer M, Schneider R, Willenegger H. *Manual of Internal Fixation*. New York: Springer-Verlag, 1979:71, with permission.)

Specialized washers for fixing tendons and ligaments to bone have spiked undersurfaces. Also available are nuts with attached washers and screws. These improve fixation when the screw threads fail to gain purchase because of poor bone quality or technical error. A unique asymmetric nut is available in the Alta system (Fig. 11.33).

**Figure 11.33.** This Alta nut is usually used to lock two plates together in the system, but it can be used free as a washer-nut on the opposite cortex to enhance fixation in soft bone. The rectangular shape enhances delivery to the tip of the screw and increases the binding to the opposite surface (magnified).
INSTRUMENTS AND TECHNIQUES FOR SCREW INSERTION

DRILL POINTS
Drill points (Fig. 11.27 and Fig. 11.29) must be sharp and straight. Dull drill points will overheat and “kill” bone. This can lead to premature mechanical failure of fixation and also predisposes to infection. Bent drill tips wobble, producing a hole larger than that required for the screw and thereby compromising fixation. When a dozen or more drill holes are made during a fixation procedure, drill points become dull and usually need to be replaced for the next procedure. If a drill point is inadvertently run against a metal surface such as a retractor, replace it, as dulling of the tip compromises its cutting power and can overheat bone. Use the proper-diameter drill point for each size of screw used. For cortical screws, use a drill point equal to or slightly larger than the core diameter of the screw. To produce a lag effect with cortical screws, use a drill point equal to or slightly larger than the outside diameter of the threads in the near cortex. For the screws used in the AO systems, the appropriate sizes of drill points are shown in Fig. 11.27 and Fig. 11.28.

POWER SOURCE
For screw fixation, hand drills are not as effective as power drills, primarily because the wobble introduced by hand drilling produces a slightly larger hole than desired. Power drills offer more precision and are preferred. The major danger with both hand and power drills is overheating due to excessive drilling speeds, particularly if drill points are dull. High-speed drills designed for inserting wires or for use with high-speed burrs are not suitable for inserting screws. The usual drilling speed for drill points is 600 to 700 rpm. To avoid bone necrosis, continually cool the drill point during drilling by irrigation with sterile saline. If drilling is prolonged, withdraw the drill point and frequently clean its flutes of bone.

The soft tissues around bone, particularly neurovascular structures, must be protected during drilling. In addition, avoid scratching fixation devices such as plates. To protect soft tissues and plates, use drill sleeves over the drill point. Drill sleeves also give better purchase on bone and increase the accuracy of drilling.

Proper drilling depth is established through practice. As a drill point begins to exit a cortical bone surface, it slows slightly and the pitch of the drilling sound changes. Use this as a signal to ease pressure on the drill, and prepare to arrest the forward motion of the drill to avoid overpenetration.

MEASURING SCREW DEPTH
Some drilling systems provide measurements on the drill shaft to determine screw length, but for the most part separate depth gauges are used (Fig. 11.34). Incorrect measuring can occur if you accidentally hook only the near cortex, or hook soft tissues or a bone surface other than the one desired, on the far side. In addition, improper mounting of the measuring tine in the depth gauge can produce erroneous measurements. After insertion of screws, always verify appropriate screw lengths either by palpation or by intraoperative radiographs, and check the depth gauge if lengths are inappropriate. In most situations, the appropriate screw length is such that one full thread exits the far cortex. This is
unnecessary with cancellous screws in most applications and in fact may be inadvisable where the sharp tip of the screw threatens soft tissues on the opposite side of the bone.

There are other nuances affecting screw length to be aware of. In the AO and similar systems, cortical screws are generally available in 2 mm increments. The depth gauge measurement is designed to place just one thread of the tip of the screw through the opposite cortex when the screw head is fully seated. If measurement indicates an odd number, such as 21 mm, then the next larger screw is used, in this case 22 mm. This ensures that the maximum number of threads is always engaging the far cortex.

In self-tapping screw systems, such as the Alta system, 3 mm or so of the tip of the screw is made up of the flutes, which are a part of the self-tapping feature. To be certain that a maximum number of screw threads engage the far cortex, depth gauges in these systems usually compensate for this and provide a measurement that allows approximately 3 mm of the screw tip to protrude beyond the far cortex. In addition, self-tapping screws are more frequently available in titanium systems where the plates being used are quite flexible and conform much more closely to the bone than steel. This may result in the screw tip protruding through the opposite cortex 5 mm or more, particularly in the first several screws used to fix the plate to the bone. Therefore, it is important to check the screw lengths by either palpation or radiographic visualization after completion of insertion of all screws in the plate, as it may be necessary to replace them if excessive length of the tip beyond the opposite cortex poses a problem. Penetration of 5 mm or so in many locations where the screw tip is well buried and not in the vicinity of neurovascular structures presents no problem; if the screw tips are on a subcutaneous border beneath skin, however, they can be quite bothersome to the patient and must be adjusted. If an in-between-size screw is needed in these systems, choose the next smaller screw, rather than the next longer screw as in AO system.

**TAPPING**

If a self-tapping screw is used and excessive torque is required to insert it, back it out, clean the flutes, and readvance the screw. This avoids microfractures of the bone. Very
dense cortical bone may require tapping of the near cortex. The screws most commonly used require tapping (Fig. 11.29). The correct tap for a given screw diameter must be used. In the AO system, a short tap is provided where lag screw fixation with cortical screws makes tapping of the near drill hole undesirable. Tapping can be done by hand or with power. To avoid microfracture of the bone and breakage of the tap, reverse the tap for a half turn every several terms to clear bone chips. Use low rpm settings and frequent reversals if tapping with power.

**SCREWDRIVERS**

Many different screwdriver bits and heads are available, but the most commonly used are hex-socket-type heads and modified cruciate heads, in which the tines are rounded at the corners. Many names are applied to the latter tips, but they are most often referred to as Woodruff tips. A standard industrial screwdriver tip recently introduced is the Torx used in the Alta system. It provides superior driving torque, particularly in titanium alloy screws. It fits snugly into the screw, providing a self-retaining feature that is helpful in screw placement.

When driving screws, maintain axial alignment to the hole drilled. Once the medullary canal is entered, it is possible to miss the opposite drill hole. Inexperienced surgeons should always drive screws by hand; hand-driving is also necessary when the bone quality is poor. A power driver with a screwdriver tip is useful when multiple screws are being inserted into cortical bone, but this technique requires experience.

Make screws snug but avoid overtightening, which can result in fracture of the bone or failure of the screws. Overtightening also predisposes the screw to premature failure. In healthy young cortical bone, it is generally recommended that about 25 inch-pounds be applied to the screw. This can be learned by using a torque screwdriver; experienced surgeons can sense the appropriate tightening of a screw.

**SURGICAL TECHNIQUES**

**LAG SCREW FIXATION**

Whenever a screw crosses two bone surfaces, as in a fracture or osteotomy, use the principles of lag screw fixation (Fig. 11.35):

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**Figure 11.35.** Lag screw fixation. A: Overdrilling the near cortex produces a “lag” effect and interfragmentary compression. B: Threading both cortices leaves a gap between the two bone fragments. (From Müller ME, Allgöwer M, Schneider R, Willenegger H. *Manual of Internal Fixation*. New York: Springer-Verlag, 1979:37, with permission.)
• For effective interfragmentary compression, overdrill the cortex adjacent to the screw head, so thread purchase is achieved only in the opposite fragment.

• Notice that threading both fragments produces persistent distraction between the fragments.

When fixing a plate to bone where the screw does not cross a fracture or osteotomy interface, better purchase is obtained by bicortical fixation. In rare circumstances, it is undesirable to reduce the distance between two bone surfaces; the classic example is in fixation of the distal tibiofibular syndesmosis. In this situation, it is undesirable to overcompress the joint between the tibia and the fibula after reduction has been achieved. Instead, use a fully threaded cortical screw in each of the four cortices of the tibia and fibula, engaging all cortices with threads. To achieve lag screw fixation with cortical screws, two techniques are available, depending on which screw hole is drilled first: the gliding hole or the threaded hole.

**Gliding-Hole-First Technique**

• In simple fractures where most of the fracture line is visible, reduce the fracture anatomically and hold it with bone-holding forceps.

• To provide optimal alignment between the screw holes and to prevent displacement of the fracture as the screw is tightened, insert one or more interfragmentary lag screws, drilling the gliding hole first, then placing a drill sleeve and drilling the threaded hole (Fig. 11.36).
- Protect the soft tissues by using a 4.5 mm tap sleeve as a drill guide. Drill the gliding hole in the near cortex with a 4.5 mm drill bit (Fig. 11.36A).

- Insert a drill sleeve into the hole until it makes contact with the opposite cortex. This sleeve has an outer diameter of 4.5 mm and an inner diameter of 3.2 mm (Fig. 11.36B).

- Drill the opposite cortex with a 3.2 mm drill bit (Fig. 11.36C).

- Use a countersink to create a recess for the screw head in the near cortex (Fig. 11.36D).

- Use the large depth gauge to measure screw length (Fig. 11.36E).

- Tap the drill hole in the opposite cortex with the short 4.5 mm tap (Fig. 11.36F).

- Insert the correct-length 4.5 mm cortical screw until the fracture site is snugly approximated. If more than one screw is to be placed across a fracture, do not completely tighten the screws until they are all in place (Fig. 11.36G).

When the fracture site is not well visualized, or when the configuration of the fracture or osteotomy will make accurate screw placement difficult, drill the gliding hole first either from the outside or inside in the near bone fragment before reducing the fracture. This permits precise placement of the drill hole, which ensures that the screw does not enter the fracture line and that adequate bone stock is available for purchase (Fig. 11.37).
Locate the appropriate site in one bone fragment for the gliding hole. Drill the hole using the 4.5 mm drill through a tap sleeve (Fig. 11.37A, Fig. 11.37B).

More accuracy can sometimes be obtained by drilling from inside to outside (Fig. 11.37B).

Reduce the fracture, insert the drill sleeve, drill the threaded hole, and complete the screw fixation (Fig. 11.37C).

**Threaded-Hole-First Technique**

- Where it is not convenient to make the gliding hole first, drill the threaded hole with the 3.2 mm drill bit inside to outside first (Fig. 11.37D).

- Insert the pointed drill guide into this hole (Fig. 11.37E).

- Reduce the fracture, place a 4.5 mm tap sleeve through the sleeve of the pointed drill guide, and drill the gliding hole with a 4.5 mm drill, taking care to maintain appropriate alignment. While maintaining reduction, insert a screw and complete the fixation (Fig. 11.37C, Fig. 11.37D and Fig. 11.37E).

**Lag Screw Fixation of a Spiral Fracture**

Figure 11.38 illustrates the principles applied to the fixation of a long, spiral fracture. In general, lag screw fixation of an oblique or spiral fracture requires neutralization by a plate if sufficient stability is to be achieved to allow immediate rehabilitation without external protection. In very long or oblique diaphyseal fractures, and in some similar fracture configurations in the epiphysis and metaphysis, it may be possible to achieve good fixation with lag screws alone. When only lag screws are used, however, external protection with a functional brace and delayed weight bearing are advised. For fixation of a noncomminuted
diaphyseal fracture with lag screws alone, the fracture length must be at least three times the diameter of the shaft at the site of the fracture.

Place screws at right angles to the fracture lines in each section of the fracture to obtain maximum interfragmentary compression. Proper placement avoids shear stresses that will cause the fracture to slide on itself. In spiral fractures, this requires the screws to spiral down the fracture site. In addition, in most fracture configurations, the screws are best placed at right angles to the long axis of the shaft of the bone, because longitudinal compressive forces will cause the screws to tighten rather than loosen.

**FIXATION OF ARTICULAR FRACTURES**

Internally fix fractures in the epiphyseal and metaphyseal regions with cancellous screws and washers, using lag screw fixation. At least two (often three) screws are required to prevent the fragments from rotating. Unless the bone is osteoporotic, cancellous screws need not exit the opposite cortex. In fact, in articular locations this is usually inadvisable because the sharp tip of the screw may impinge on neurovascular structures or present an uncomfortable prominence under the thin skin over joints. A typical configuration is shown in Fig. 11.39.
Figure 11.40 shows the application of 4 mm cancellous screws to internally fix an intraarticular fracture of the talus in an immature limb. Note that the two screws are perfectly parallel because the drill holes were placed with the pointed drill guide, which guarantees parallel drill holes. This is important for optimal lag effect. Figure 11.41 shows similar screws used in a more common application, a displaced fracture of the medial malleolus. Again, the pointed drill guide is used to ensure that the screws are parallel. The versatility of interfragmentary cancellous screw fixation is shown in Fig. 11.42, in which a displaced acetabular fracture is fixed with three screws because it was inconvenient to place a plate. As described, nontapped cortical screws also work very well in the pelvis if the fracture surfaces are well compressed by bone-holding forceps.
When intraarticular fractures in cancellous bone, such as a vertical spilt fracture of a lateral tibial plateau, are fixed with interfragmentary screws alone, vertical shear forces tend to displace the condyle inferiorly. This can be neutralized by placing a buttress screw to support the fragment. Either a cancellous or a cortical screw can be used, depending on the location of the fracture and the quality of the bone.

- Place a drill hole immediately adjacent to the inferior tip of the proximal fragment, and drill in a bicortical fashion at right angles to the longitudinal axis of the tibia.

- Then place a screw with a washer. Be certain that the screw shaft contacts the tip of the fragment and the washer is brought snugly against the inferior spike of bone. This will prevent inferior shift of the fragment (Fig. 11.43).

**Figure 11.42.** Internal fixation of a complex fracture of the acetabulum using only cancellous lag screws. Although these were sufficient in this patient, in some fractures plate fixation would be required as well.

**Figure 11.43.** Buttress screw (antiglide screw). Insert at the tip of the condylar fragment with the washer overlapping the proximal fragment, to prevent inferior subsidence of the condyle.

**SPECIALIZED SCREWS**
DOUBLE-THREADED SCREWS
The Herbert screw is another implant used for interfragmentary compression. Threads are present at both ends of the screw, with a pitch differential between the leading and trailing threads. Interfragmentary compression is achieved by the difference in thread pitch, so a screw head is not required. The absence of a screw head makes it possible to insert Herbert screws through articular surfaces without the head being prominent. Originally designed for scaphoid fractures, current indications include osteochondral fractures, osteochondritis dissecans, capitellar fractures, radial head fractures, and small joint arthrodesis. A disadvantage is that the Herbert screw can be difficult to remove. The Herbert screw used in an illustrative case is shown in Fig. 11.44.

![Figure 11.44. Internal fixation of osteochondritis dissecans by Herbert screws. The trailing thread is countersunk beneath the articular surface of the medial femoral condyle.](image)

CROSSLOCKING SCREWS
Strong screws are required for interlocking of intramedullary nails. Most systems use a smooth-shanked screw with special features to ease removal (Fig. 11.45).

![Figure 11.45. Crosslocking screw. Note the thick shank and low profile thread to enhance strength.](image)
CANNULATED SCREWS

Cannulated screws have a hollow core that allows screw insertion over a previously placed guide wire (Fig. 11.46). Potential benefits of this system are less soft-tissue dissection and the presence of a guide wire for provisional fixation and for accurate screw placement (Fig. 11.47). These screws are most often used for percutaneous fixation or femoral neck fractures, where fluoroscopic imaging of guide-wire placement helps to ensure appropriate screw length and screw position. Placement requires initial placement of a guide wire. A hollow drill is used over the guide wire and a cannulated tap is used if required. Cannulated screws are best inserted under fluoroscopic control. A depth gauge or measurement from a calibrated drill bit determines the length of screw to be used.

Figure 11.46. A cannulated screw can be inserted over a previously placed guide wire.

Figure 11.47. Intraoperative radiograph of internal fixation of medial malleolus fragments using cannulated screws. The guide wires are helpful in achieving and maintaining the reduction of the fracture until screw insertion is completed.
The disadvantages are that the screws are weaker than noncannulated screws, particularly in the small fragment size, and they break more easily when removal is attempted (Fig. 11.48).

Figure 11.48. Percutaneous internal fixation of a femoral neck fracture with multiple cannulated screws.

**ABSORBABLE SCREWS**

Polylactic acid and other polymers are now used to manufacture absorbable screws. Indications include children when hardware removal can be avoided, and in the internal fixation of juxtaarticular fractures such as those of the medial malleolus, where high strength is not required and removal of hardware is often required because of the subcutaneous location of the screw. Bucholz et al. (23) have described good success with absorbable screws.
**FIXATION OF TENDONS AND LIGAMENTS**

Ligaments and occasionally tendons can be attached to bone for repair or reconstruction using a cancellous bone screw driven through the soft-tissue structure, with a spiked washer to obtain purchase on the ligament or tendon. Although this works well, one disadvantage is that the area of soft tissue fixed with the screw and washer becomes avascular due to the pressure. Sometimes this avascularity will lead to failure of fixation before adequate soft-tissue healing.

Other ingenious techniques have been devised to secure ligaments and tendons to bone, either by bone blocks or by indirect fixation. Daniel et al. described a step-cut tibial channel to capture the tendon preparation (35). Sutures are passed through the tendon preparation using a double-loop technique and are then tied to the head of a cancellous screw (Fig. 11.49). The interference screw technique (Fig. 11.50) described by Lambert is easier to perform and in my opinion provides better fixation (65).

**Figure 11.49.** Step-cut tibial channel for fixation of a bone ligament preparation for reconstruction of the anterior cruciate ligament. Sutures placed through the bone–tendon preparation by double-loop technique are tied to the head of a cancellous screw. (From Daniel DM, Robertson DB, Flood DL, Biden EN. Fixation of Soft Tissue. In: Jackson DW, Drez D Jr, eds. *The Anterior Cruciate Deficient Knee.* St. Louis: CV Mosby, 1987, with permission.)

**Figure 11.50.** Interference-fit fixation of the bone plug on a bone–tendon preparation for reconstruction of the anterior cruciate ligament using a 30-mm-long, 6.5-mm-wide cancellous screw. Fixation depends on a snug fit of the bone plug in the drill hole. (From Lambert KL. Vascularized Patellar Tendon Graft with Rigid Internal Fixation for Anterior Cruciate Ligament Insufficiency. *Clin Orthop* 1983;172:885, with permission.)
**SUTURE ANCHORS**

Since the previous edition of this book, a large number of suture anchors have become available that are based on the molly bolt principle or that are screws. Sutures of various sizes and materials are attached to these devices. When needing to attach ligament, tendon, or capsule to bone, these devices are inserted into the cancellous bone at the attachment site, securing the suture to the bone, which is then used to attach the soft tissue (Fig. 11.51). These have offered significant improvements, particularly where arthroscopic repairs are performed.

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**E. PRINCIPLES OF PLATE FIXATION**
Except for simple lag screw fixation, plates are probably the oldest means of fracture stabilization. Many types of plates have been applied to bone, some by screws, others with the help of wire loops. However, not until Danis in 1949 were plates applied with axial loading (compression) of the bone and fracture underneath (36). It was observed that this type of compression fixation leads to fracture healing without visible external callus (soudure autogène, or direct bone healing). From this observation, in the late 1950s, Müller developed the original AO round-hole compression plate with the removable compression device. Bagby and Janes developed a similar plate (7,8). Since that time, plating has become a well-established means for fixation of a large variety of fractures and nonunions, and many different plate designs, forms of application, and plate functions have been described. For a review of the literature, see The Dynamic Compression Plate by Allgöwer et al. (2).

Although there is virtually no fracture that could not in principle be fixed with a plate, other devices for fracture fixation, such as the interlocking nail and the external fixator, have advantages over plates in certain situations, especially in diaphyseal fractures of the femur and tibia.

Plates may be classified according to either type (shape and size) or function. Both type and function often correspond to a specific application (for example, the L-shaped buttress plate for fractures of the tibial plateau). On the other hand, a given plate may have different functions, depending on (a) the mechanical configuration of the bone–plate conjunction, resulting in static compression, dynamic compression (tension band), neutralization, and buttressing; (b) which part of the bone is stabilized (metaphysis or diaphysis); and (c) the specific fracture configuration.

**DEVELOPMENT OF PLATE FUNCTIONS**

The original AO round-hole compression plate was thought to provide static compression of a diaphyseal fracture, thereby leading to rapid bony union, as was shown experimentally in sheep (82). After fracture reduction, compression or axial loading was applied with the help of the removable compression device. Today, it is known that in most cases the originally instituted compression force of up to 80–90 kilopascals (kp) was lost after the remaining screws were introduced into the round holes of the plate. The reason for the success of the so-called compression plate, therefore, was most probably not compression in the first place, but rather the better method of fracture fixation with newly designed implants that were also applied differently (e.g., by power drilling, pretapping). In hypertrophic nonunions, the primary achievement of the compression plate was better approximation of the nonunited fragments and optimal stabilization, allowing calcification of the interposed tissues. If properly placed on the tension side (convexity) of the nonunion, the compression plate acts as a tension band, which actually provides dynamic rather than static compression.

With increasing knowledge about the physiology of fracture healing, it became evident that to stimulate bone remodeling by creeping substitution, a signal was needed. The best way to transmit or generate this signal appeared to be physiologic loading of bone by controlled weight-bearing.
For this purpose, the original AO/ASIF (Association for the Study of Internal Fixation) round-hole plates were probably somewhat less forgiving when not ideally applied. Too much axial loading could lead to fatigue failure of the plate or loosening of the screws rather than to bony union.

In 1965, the dynamic compression plate (AO/ASIF DCP) was introduced. The self-compressing effect by eccentric screw placement, combined with the possibility of a gliding or sliding effect (Fig. 11.52) between the screw head and the plate hole, allowed a more physiologic force transmission within bone during weight bearing. Furthermore, thanks to the spherical configuration of both screw head and plate holes, the compression instituted initially was maintained throughout the procedure, even if the screws were not placed at a right angle to the plate.

**Figure 11.52.** A: Dynamic compression plates of different dimensions. From top to bottom: broad, 4.5 mm; narrow, 4.5, 3.5, 2.7 mm. B: Schematic representation of the spherical gliding principle of the DCP. (From Müller ME, Allgöwer M, Schneider R, Willenegger H. *Manual of Internal Fixation*. New York: Springer-Verlag, 1979:235, with permission.)

**STATIC COMPRESSION**

Static compression is best demonstrated on the model of a transverse fracture (Fig. 11.53). Tensile pre-stressing of a straight plate produces axial compression in the fracture. The area underneath the plate is compressed, while the opposite cortex shows a gap. To increase the amount of bone surface being compressed (including the opposite cortex), it is advisable to contour the plate to approximate the cortex opposite the plate. Another possibility to prevent a slight gapping of the osteotomy or fracture line in the far cortex is to place a lag screw across the fracture or osteotomy plane (Fig. 11.54).

**Figure 11.53.** Static compression in a transverse fracture (humerus) fixed with a slightly overcontoured plate. Axial compression is obtained via the removable tension device. A: Plate application with the tension device. B: Equal distribution of compressive forces. (From Müller ME, Allgöwer M, Schneider R, Willenegger H. *Manual of Internal Fixation*. New York: Springer-Verlag, 1979:223, with permission.)
Most transverse diaphyseal fractures are best treated by a medullary nail. The indications for a static compression plate, therefore, are less common; these include transverse fractures of the humerus and forearm bones.

**DYNAMIC COMPRESSION (TENSION BAND PLATE)**

From his experience in mechanics, Pauwels borrowed the principle of tension band fixation and demonstrated its application in operative fracture treatment (79). Every eccentrically loaded bone is subjected to bending stresses and deforms in a typical manner, with a gap on the convex or tension side and compression on the concave side of the bone (Fig. 11.55A). To restore the load-bearing capacity of an eccentrically loaded bone, the tensile forces on the convex side must be absorbed by a tension band (wire or plate) (Fig. 11.54). Fracture fixation is improved by placing an interfragmentary lag screw through the plate. A: Placement of interfragmentary lag screw across a 3.5 plate; drilling of a gliding hole with a 3.5 mm drill bit. B: Drilling of a threaded hole with a 2.5 mm drill bit and corresponding drill guide. C: Interfragmentary compression across plate and fracture is achieved by tightening the lag screw. (From Müller ME, Allgöwer M, Schneider R, Willenegger H. Manual of Internal Fixation. New York: Springer-Verlag, 1979, with permission.)
11.55B). The bone itself—especially the cortex opposite the tension band—must be able to withstand axial compression; this requires a medial buttress, usually supplied by the intact cortex. Thus, the implant absorbs the tension forces, and the underlying bone the forces resulting from compression. Loading (e.g., by partial weight-bearing) results in a dynamic increase of the axial interfragmental compression. In the absence of a medial buttress, which absorbs the compression forces, the plate is subjected to repeated bending stresses, which inevitably lead to fatigue failure and implant breakage (Fig. 11.55C).

Except for the femur, olecranon, and patella, it is difficult to identify the tension or compression side of a fresh fracture, but in a malunion the aspect (lateral, medial, or posterior) on which the tensile forces are most active is usually clearly visible (Fig. 11.56). The best indications for a tension band plate, therefore, are fractures in the subtrochanteric area of the femur (requiring a 95° blade plate or broad DCP), certain olecranon fractures (one-third tubular or 3.5 mm plate), and nonunions.
NEUTRALIZATION

By far the most common function of a plate is neutralizing or protecting an interfragmentary lag screw fixation (Fig. 11.57). Most fractures can be reduced by interfragmentary lag screw fixation alone (Fig. 11.57B), but in many instances this fixation will not suffice for early active movement or partial weight bearing. To protect the lag screw fixation from bending, torsion, and shearing forces, a neutralization or protection plate is added (Fig. 11.57C).

After screw fixation, carefully contour the plate and fix to the bone with all screws in a neutral position. Place a lag screw across the fracture through the plate whenever possible, as this greatly improves the neutralizing bone/plate system (Fig. 11.57C).

BUTTRESS FUNCTION

In the metaphyseal area of most bones, one encounters intraarticular fractures that are a combination of cleavage (T or Y), with or without impaction of cartilage and subchondral cancellous bone. After reconstruction of the articular surface and grafting of the bone defect, one or two buttress plates will fix the articular fragments to the shaft and support or buttress the metaphyseal area (Fig. 11.58). Typical indications for buttress plating are fractures of the distal humerus, the tibial plateau, and the tibial pylon, and compression fractures of the distal radius. Accordingly, all T and L-shaped plates are designed for buttress functions. If a DCP with gliding holes is applied for buttressing, the screws must be introduced at the end of the gliding slope to prevent further collapse.

Figure 11.57. Neutralization plate in the tibia. A: Comminuted, multifragment fracture. B: After anatomic reduction and preliminary fixation with two lag screws and a cerclage wire. C: A neutralization or protection plate has been added on the medial aspect of the tibia, with two additional lag screws through the plate (arrows). (From Müller ME, Allgöwer M, Schneider R, Willenegger H. Manual of Internal Fixation. New York: Springer-Verlag, 1979:33;581, with permission.)

Figure 11.58. Buttress plates in tibial plateau fracture. A: Bicondylar plateau fracture with impaction of lateral articular surface. B: Reduction and stable fixation with two buttress plates: L or T plate laterally, tubular plate medially. (From Müller ME, Allgöwer M, Schneider R,
Weber described a special kind of buttress plate, an antiglide plate (107). For this purpose Weber usually applies semi- or one-third-tubular plates in such a way as to prevent the tip of an oblique fracture from displacing due to muscle pull. For example, in a type B fracture of the lateral malleolus (Fig. 11.59), the three-hole, one-third-tubular plate is placed posteriorly and thereby locks the tip of the distal fragment into an anatomically correct position.

**PHYSIOLOGY OF PLATE FIXATION**

Before the revolution in plate fixation was started by the AO Group in the late 1950s, the major problems encountered in plate fixation of fractures, other than the usual surgical complications, were early plate failure, screw breakage, and screw pullout. Plates were relatively weak, and the principles of obtaining a biomechanically stable reconstruction through improvements in interfragmentary contact were not yet well known. Screws were still based on designs from the woodworking and metal industries, and their thread designs were not ideal for fixation in bone. In addition, most screws were self-tapping; this self-tapping feature was not well designed and led to microcracks, which hindered the hold of the screw in bone.

The introduction of the much more rigid fixation obtainable with AO implants led to a new set of clinically significant problems: bone loss under the plate, fracture at the ends of the
plates, or refracture through the fracture site or screw holes after plate removal. Anderson et al. (5) and Hidaka and Gustilo (52) had a 22% incidence of refracture after plate removal using the standard, narrow 4.5 mm AO plate on fractures of the radius and ulna. Chapman et al. (27) were able to eliminate refractures in plate fixation of the radius and ulna by using the AO/ASIF 3.5 mm system.

Laboratory investigation of this problem has shown two possible causes: stress protection, and devascularization followed by revascularization. Studies by Woo et al. (115), Coutts et al. (32), Uhthoff and Dubus (103), and others demonstrate that stiff plates, when applied to healing fractures, result in weaker fracture callus and, when left in place for prolonged periods, weakening of the bone under the plate due to bone resorption. These authors felt that this effect was due to "stress shielding." In accordance with Wolff's law, introducing a rigid member across a fracture site alters the signals influencing the homeostatic mechanisms controlling bone apposition and resorption, so that the fracture heals with weaker callus and bone resorption occurs under the plate and in the surrounding cortex.

Swiontkowski and Senft (102) and others have demonstrated devascularization of the cortex secondary to soft-tissue stripping and disturbance of the intrinsic blood supply to bone by the application of the plate and insertion of screws. Revascularization of the bone results in bone resorption. The hypervascularity associated with that is most evident under the plate.

Both of these factors are important, and newer plate designs have addressed both issues by producing more flexible plates from materials with a lower modulus of elasticity, such as titanium, titanium alloys, carbon fiber, or polymer, and by newer configurations. Only titanium is currently in use clinically, however.

**NEWER PLATE SYSTEMS**

Many plating systems are now available that use CP titanium, 6-4 titanium alloy (described above, in the section on Implant Materials), or other alloys. Titanium is more flexible than surgical steel, yet stronger. Howmedica (Rutherford, NJ) produces a modular bone fixation system from 6-4 titanium in an attempt to optimize the environment for fracture healing. The modular system allows plates of different lengths and types to be interconnected by dovetailing (Fig. 11.60). This modular feature reduces the need for soft-tissue stripping to place the plates. The use of larger oval holes in the plate, which will accommodate two screws, permits fixation with shorter plates and increases the range of angles through which screws can be placed; this enhances fixation. The railed design of the plate limits plate contact with the bone to potentially enhance revascularization. A new plate from the AO Group known as the limited contact dynamic compression plate (LCDCP), also of titanium, is an effort to achieve the same goals (Fig. 11.61).

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**Figure 11.60.** Alta modular titanium plating system. **A:** The Alta channel plate (extension plate) features a railed undersurface, holes for single or double 5.0 mm screws, and a rounded configuration for insertion into a dovetail. **B:** The underside of an Alta distal femoral fracture plate.
New screw-thread and cutting-flute designs have eliminated the need for tapping, removing one step from the fixation process. The self-cutting threads and titanium material provide better frictional hold between the screw and bone, preventing screw backout. The new four-fluted design of the Alta screw reduces the heat of insertion and prevents microcracks of the cortex.

Considerable experimental and clinical work has been done with polymeric and carbon fiber plates as well (103). Their modulus of elasticity is even closer to that of bone, but they cannot be molded during surgery and some tend to be quite brittle. Thus far, they have not been found to be practical in clinical applications. Other efforts to make plate and screw fixation more compatible with normal bone physiology have been directed toward the development of resorbable plates and screws, or placing resorbable surfaces on the plate—

Figure 11.61. The AO titanium low-contact dynamic compression plate. Its unique configuration offers fewer stress concentration points and less contact with bone to enhance preservation of the blood supply to bone.
bone or plate–screw interface. Resorption results in eventual loosening of the construct, thereby allowing more physiologic transmission of stresses. All of these are experimental at present and have not entered clinical practice.

GENERAL PRINCIPLES OF PLATE FIXATION

LOCATION
Earlier in this chapter, I emphasized that plates should be used as tension bands if possible and therefore placed on the convex surface of bones. This is particularly true for the radius, where plates are usually placed on the dorsal lateral surface, and for the femur, where they are placed anterolaterally. In the humerus, plate location is dictated more by the anatomy of the surgical exposure, and generally the plate is placed laterally or dorsally. The bending forces about the tibia are less predictable, but generally plates are best placed on the lateral surface because of the excellent soft-tissue coverage provided. In general, try not to place plates in subcutaneous locations, as skin slough or infection may result in plate exposure. In addition, plates in subcutaneous locations are more likely to produce symptoms. However, the practical aspects of fixation demand placement of plates in subcutaneous locations in some circumstances, such as plating of the olecranon and the lateral malleolus.

SURGICAL TECHNIQUES

EXPOSURE
The following principles apply to fixation of most diaphyseal fractures with plates:

- When exposing the fracture, limit soft-tissue stripping to just the surface on which you expect to place the plate. Avoid the use of retractors and bone-holding forceps, which require circumferential stripping of bone. Fine-pointed tenaculum-type bone-holding forceps are best.

- There seems to be no advantage to leaving the periosteum intact beneath the plate. For most plates in common use today, application of the plate on the periosteum results in complete loss of blood supply to the periosteum. In addition, the fixation of the plate to bone is less secure, due to the intervening soft tissue. It is more difficult to obtain an anatomic reduction, particularly in comminuted fractures. On the other hand, maintaining soft-tissue attachments to bone is important. Newer "point contact" plates may change this advice.

- If very small butterfly fragments are involved, maintaining soft-tissue attachments to the butterfly may make the fixation of the fracture exceedingly difficult and may result in less-than-optimal reduction. In such cases, I do not hesitate to detach small bone fragments from soft tissues to enhance the ability to obtain fixation. These small fragments usually revascularize very quickly.

- To ensure that bone union occurs in the presence of such comminution, however,
apply a cancellous bone graft across the comminuted zone.

- Accurate reduction and apposition of butterfly fragments is particularly important when their absence would leave a gap opposite the plate. This dramatically increases the bending stresses on the plate and could lead to early fatigue failure of the plate.

- After exposing the fracture site, clean the fracture ends of all organized hematoma and soft tissue. Strip the periosteum from the fracture ends 1–2 mm, just enough to delineate the fracture surface.

REDUCTION AND PLATE APPLICATION

Transverse fractures that are inherently stable can be reduced before plate application, and this simplifies fixation. Unstable fractures pose a challenge, particularly if excessive soft-tissue stripping is to be avoided. In simple oblique or spiral fractures, or those with small butterfly fragments where there is good cortical contact, often the fracture can be reduced with a small tenaculum forceps and preliminary fixation obtained with an interfragmentary lag screw. Application of the plate then is simplified. In more unstable and comminuted patterns, a different approach may be necessary. If a major butterfly is present, the best approach may be to fix the butterfly to one fragment with an interfragmentary lag screw, which then may produce a stable pattern that can be reduced and easily plated. If this is impossible, I advise using the plate to provide the mechanism for reduction of the fracture:

- Precontour the plate, select the approximate location for the plate, and choose the point for the first screw hole on one side of the fracture. If necessary, lay the plate on the surface of the bone on one side of the fracture and mark the site for the screw with a methylene blue marking pen.

- Drill for the screw without the plate in place, and then secure the plate to one fragment with one screw.

- Tighten the screw to achieve reasonable stability, but do not overtighten it, as this may interfere with the reduction. Then reduce the fracture and stabilize it using a tenaculum or small plate-holding forceps on the side of the plate not attached to bone.

Fixation of the plate to one side of the fracture before reduction is immensely helpful. This avoids the common struggle in which the fracture is reduced and held with multiple bone forceps, but then the surgeon finds that the plate cannot be placed. Removing the forceps to place the plate then results in loss of stability, and a prolonged struggle ensues to hold the reduction while applying the plate.

INDIRECT REDUCTION TECHNIQUES
For very comminuted fractures, such as in the supracondylar region of the femur and in pylon fractures, use indirect reduction techniques as popularized by Mast to avoid devascularization of the many bone fragments (71). To achieve length, apply a femoral distractor and then use it to pull the fracture out to length; or, fix the plate to one fragment and use the plate itself to distract the fracture out to length, using the outboard plate compression device or a lamina spreader between the end of the plate and an outboard screw.

- With distraction, nudge the intercalary comminuted fragments into reasonably good position.
- With severe comminution, achieve good plate fixation above and below the fracture, but do not attempt fixation of the multiple small fragments. Application of a bone graft to the comminuted section through the fracture site, prior to reduction, to accelerate union may be wise.
- In small, good-quality bones, apply screws through five or six cortices (up to three bicortical screws) for fixation on either side of the fracture. In the humerus, tibia, and femur, use solid bicortical fixation through the cortex, with four screws on each side of the fracture. In long spiral or oblique fractures, some of these screws should be interfragmentary lag screws.

**WAVE PLATES**

Another interesting method for plate fixation popularized by the AO group and recently used successfully by Jupiter et al. (33,55) is the wave plate. Although this is potentially applicable to acute comminuted fractures in a technique similar to that described previously as an indirect reduction technique, for the most part it has been limited to the treatment of nonunions of the diaphysis of large bones such as the humerus and femur.

- Contour a large broad plate to fit the bone proximally and distally to the nonunion site, producing a wave in the plate that lies free of the cortex and bypasses the nonunion site and fracture callous (e.g., in hypertrophic nonunions). Solidly fix this to the proximal and distal fragments with at least four bicortical screws above and four below. Then pack bone graft around the nonunion site, including the area beneath the plate.

The principle of this technique is that it requires minimal stripping of soft tissues around the nonunion site and, therefore, maximally protects vascularity. In addition, it makes available the largest surface area for revascularization. The major disadvantage of the technique is that it does not provide nearly as secure fixation as more rigid techniques such as the double plates described below. If the patient bears excessive weight on an unstable nonunion site, premature fracture of the plate through one of the empty screw holes in the wave section can occur.
DOUBLE PLATES
For simple fractures, I do not use double plates: Their application requires too much soft-tissue stripping, and the rigid fixation produced may cause stress protection osteopenia. Indications for double plates are difficult nonunions, particularly where bone quality is less than optimal, and fracture configurations where solid bone contact on the cortex opposite a single plate is impossible. Typical examples are subtrochanteric and supracondylar fractures of the femur. A second plate should always be smaller, both in overall size and length, than the major fixation plate, and it should be substantially shorter to avoid a stress riser at the end of two plates of similar length. The strongest construct is when the plates are placed at right angles to each other. For example, in the subtrochanteric region, after fixation with a hip screw with a side plate, use a four- or six-hole narrow 4.5 mm plate. In the supracondylar region, a similar principle applies, and even a small fragment plate can be used (Fig. 11.62 and Fig. 11.63).

Figure 11.62. Double plate fixation of an intertrochanteric fracture.

Figure 11.63. Reconstruction of a supracondylar fracture of the femur with double plate fixation using a 95° condylar screw with an extension plate laterally and a broad plate anteromedially. Note that the anteromedial plate is shorter than the lateral plate to minimize the stress at the upper ends of the plates.
After fixation of a fracture with a single plate, always stress the fracture to see if micromotion occurs through the fracture site. If it does, either interfragmentary screw fixation or a second plate is usually required.

**SPECIALTY PLATES**

Specialty plates are usually designed for fixation in the metaphyseal or epiphyseal portions of the long bones, or they are designed for the spine or pelvis (Fig. 11.64). Reconstruction plates have become quite popular since the early 1990s for the fixation of fractures where bending of the plates in three planes is necessary to achieve adequate conformity to bone. The most common sites for this are the distal humerus and the acetabulum and pelvis.

*Figure 11.64.* A: The 3.5 mm AO reconstruction plate is used for fibula, radius, ulna, pelvis, and other metaphyseal fractures. B: AO tibial lateral buttress plate for fixation of fractures of the tibial plateaus. The plate is thick in the diaphyseal portion and thin in the metaphyseal section. C: An AO miniplate for small bones. (Courtesy of Synthes, Paoli, PA.)
The notched reconstruction plates bend easily in all three planes. Make bends in the plane of the plate before twisting or bending vertically to the plane of the plate. Apply a malleable template to the bone first. Use the template to determine the bends on the plate. Bending is less injurious to the plate and easier with the use of special bending presses. Bending is more accurate and safer if the plate is held by an assistant while the surgeon bends the plate. Bend in small increments to avoid overbending. Reverse bending of the plate substantially weakens it and is not recommended. Avoid kinking the plate. Bends are best distributed throughout the length of the plate. Make bends between the screw holes. Avoid nicking the plate, particularly in titanium, where a stress riser effect might occur.

F. PRINCIPLES OF INTRAMEDULLARY NAILING

ADVANTAGES AND DISADVANTAGES

For the diaphysis of weight-bearing bones, intramedullary nailing is a fixation method superior to plates or external fixation, because the location of the rod in the intramedullary
canal virtually guarantees proper axial alignment. Rotational alignment can be ensured with interlocking screws. In stable fractures, weight bearing is not only feasible but preferable; in an intramedullary location, nails, unlike plates and external fixation methods, are load-sharing devices, being subjected to small, bending loads. Breakage of intramedullary implants is thus minimized. Intramedullary nails can be placed using percutaneous closed techniques that minimize soft-tissue dissection, thereby decreasing the risk of infection. An additional advantage of intramedullary nails is that removal is often unnecessary. When needed, removal can usually be done from one end of the nail, using a small incision. Refracture after removal is uncommon, as no significant stress riser is left in the bone.

One disadvantage of intramedullary nailing is the fact that the size of the intramedullary canal may limit the size of nail that can be used; this limits the bending strength of the nail unless extensive reaming is performed. Intramedullary nails without cross-locking screws do not provide as good rotational control as do plates or external fixation. Intramedullary nails, particularly reamed nails, interfere with the endosteal blood supply, which makes up to 90% of the vascular supply to the diaphysis of long bones. This disadvantage may be minimized by using nonreamed and fluted nails. In closed fractures, the clinical significance of this disadvantage is limited, since revascularization from the surrounding muscle takes place rapidly (84,85 and 86). In open fractures, particularly of the tibia, in which stripping of the periosteum and muscle and bacterial contamination occur, the risk of infection in devascularized bone subjected to intramedullary nailing is significant. In addition, the techniques for inserting intramedullary nails by closed technique can be technically demanding.

**EFFECTS OF NAILING AND REAMING ON BONE AND SYSTEMIC PHYSIOLOGY**

Reaming of the medullary canal and intramedullary nailing embolizes marrow contents into the general circulation and results in microembolization to many solid organs including the lung. In addition, there are dramatic acute effects on the diaphyseal blood flow (87).

Embolization of fat and marrow elements into the general circulation through the copious venous channels in the bone marrow has been demonstrated in animals (69,101), and embolization has been demonstrated in humans by transesophageal echocardiography and other measures (80,109). The degree of embolization is influenced by various factors (38,51). Nearly all manipulations of the intramedullary cavity cause some increase in pressure; however, Duwelius et al. (38) have shown the highest pressures with insertion of an awl into the medullary canal to open it. Reamer design can greatly influence pressurization of the canal. The lowest pressures can be obtained by using reamers with a small shaft diameter relative to the diameter of the cutting flutes, and where the design of the flutes optimizes depressurization of the canal. The presence of a fracture, slowing the rate of progression of the reamer down the canal, and increasing the rotational speed of the reamer have been found to reduce the intramedullary pressure and amount of embolization. Vent holes in the distal femur have not been shown to reduce reaming pressures reliably.
Whether this embolization is of clinical significance is controversial. Pape et al. (75) and Kröpfl et al. (62) have expressed the view that embolization of marrow contents to the lungs in patients with severe multiple injuries in whom there is pulmonary compromise or where there has been direct lung trauma is of concern; therefore, they recommend the use of nonreamed nails in patients with severe multiple injuries and/or pulmonary compromise. Many other investigators, however, have shown only transitory changes in pulmonary function in animals (92,114). Other investigators in well-designed prospective randomized and multi-institutional studies have not been able to demonstrate any significant adverse effects of reamed nailing in multiply injured patients with and without pulmonary compromise (17,109).

In view of this concern, surgeons should use instrumentation and techniques to minimize the amount of marrow and fat embolization. In addition, using caution in patients with severe pulmonary trauma or preexisting compromise of pulmonary dysfunction is wise.

The blood flow to the diaphysis of long bones can be reduced to one third of normal by reaming initially; however, this stimulates a strong hyperemic reaction that in experimental animals can reach several times normal by 2 to 4 weeks after fracture (49,76). Revascularization of the cortex occurs by reversal of the normal centrifugal blood supply to a centripetal supply coming from the surrounding muscle and periosteum. Nails that fit the cortex tightly interfere with this revascularization, so the use of smaller or fluted nails enhances reestablishment of blood supply to the marrow cavity and cortex (44,45,114). In reamed intermedullary nailing, the fracture healing process is dependent on revascularization of the diaphysis from the surrounding soft tissues; therefore, reamed nailing is potentially more dangerous to bone, particularly if infection intervenes and the soft-tissue envelope is compromised. The hyperemic response in the bone is echoed by increase in the blood flow to all the soft tissues of not only the injured leg but the contralateral extremity as well (4,6). In open fractures of the tibia with exposed bone, muscle flap coverage of a devascularized cortex has been shown to be important to revascularization and bone union (88,89,95). The hyperemic response to renailing, however, leads to high rates of union in the tibia and femur reported up to 98% (16,22). This has led to arguments about whether reamed or unreamed nailing is the best procedure for diaphyseal fractures. Schemitsch et al. (93,94) showed no difference between these two types of nailing in an animal model, from the standpoint of the vascular profusion of the bony callus formed at the fracture site at up to 12 weeks and in the strength of union of the callus. On the other hand, studies by this same research group showed that, in a canine fracture model, overall tibial blood flow was reduced by 63% with limited reaming and 83% with full reaming. These data suggest that in severe open fractures, in particular of the tibia, the best of all worlds may be achieved by gentle, limited reaming to provide maximum protection to the blood supply but still allow the use of a 10 mm or larger nail, which provides adequate mechanical strength for union in the vast majority of cases.

**TYPES OF NAILS**

**REAMED NAILS**

The classic reamed nail is the hollow, open-section nail of Küntscher (45,49). Most other
reamed nails are variations of the Künscher nail, such as the AO nail, and the various interlocking nails, such as the Grosse-Kempf (Howmedica, Rutherford, NJ), Klemm (Richards, Memphis, TN), Alta (Howmedica), Russell-Taylor (Richards), Uniflex (Biomet, Warsaw, IN), AO Universal (Synthes, Wayne, PA), and others (Fig. 11.65) (40,57,71). Fluted nails, such as the Sampson (Zimmer, Warsaw, IN), are little used since the introduction of more advanced locking nails (1). Reaming provides a precise fit for the nail in the intramedullary canal, thereby reducing the incidence of nail incarceration and improving the stability of fixation. Reaming permits the use of larger nails, which are stronger than smaller ones. A nail with a 12 mm diameter is 1.25 times stronger in bending than one with an 11 mm diameter.

**Figure 11.65.** A: Intramedullary nails that require reaming. (1) A Künscher nail, designed for open nailing, which is straight, nontapered, and slotted throughout. (Courtesy of Zimmer, Warsaw, IN.) (2) A Künscher nail, designed for closed nailing, which has a curved, tapered tip, and is slotted throughout. (Courtesy of Howmedica, Rutherford, NJ.) (3) A Grosse-Kempf nail with a curved, tapered tip, a closed section at the upper end, an oblique cross-locking screw proximally, and two transverse cross-locking screws distally. (Courtesy of Howmedica, Rutherford, NJ.) B: Alta intramedullary locking nail for the femur. This is a solid-section, cannulated nail with a hexagonal cross section with smooth flutes to enhance revascularization. It is made of a titanium alloy. Two transverse 5.0 mm diameter cross-locking screws are used distally and proximally, eliminating the need for right and left nails. (Courtesy of Howmedica, Rutherford, NJ.)

**NONREAMED NAILS**

Single, nonreamed, nonlocking nails have been designed for most of the long bones, including the femur [the Schneider nail (97) and the Hansen-Street nail (100), both no longer manufactured], the tibia [the Lottes nail (Howmedica, Rutherford, NJ) (67)], the humerus [the Sampson nail (1)], and the forearm [the Sage nail (Smith Nephew Richards, Memphis, TN) (91)] (Fig. 11.66). Single, nonreamed nails are simple to insert and are associated with improved preservation of the endosteal blood supply and rapid revascularization (71,73,84). Their disadvantages include an increased likelihood of impaction during driving and, because smaller nails must be used, their relative weakness, particularly in bending.

**Figure 11.66.** Intramedullary nails designed to be used as single nails without reaming. (Note: illustrations are not proportional.) A: A Schneider nail with a solid, four-fluted cross section and self-broaching ends. (Courtesy of Howmedica, Rutherford, NJ.) B: A Harris condylocephalic nail that is made from a titanium alloy (Ti-6A1-4V), curved in two planes, and designed for percutaneous, retrograde...
Some nonreamed intramedullary nails are designed to be used in groups. The best example is Rush rods, which have been designed for all the long bones of the body (Fig. 11.67) (90). Ender pins have a similar design (Fig. 11.68) (39,40,73,74). Multiple Steinmann pins and Kirschner wires can also be used as intramedullary nails. These devices have all the advantages of nonreamed single nails, but provide better rotational control; as a cluster, they are generally stronger than single nails. However, they are technically more difficult to use and provide relatively poor axial stability.
Several intramedullary nails, particularly for the tibia,

Figure 11.67. Rush rods are available in four diameters—
¼ inch (6.4 mm), 3/16 inch (4.8 mm), 1/8 inch (3.2 mm),
and 3/32 inch (2.4 mm)—and in a variety of lengths that are proportional to all the major long bones. Rush rods are solid, with an oblique tip and hooked end that are designed to be inserted percutaneously. These rods must be prebent by the surgeon to obtain three-point fixation in the canal. (Courtesy of Howmedica, Rutherford, NJ.)

Figure 11.68. Ender pins, which are solid with an oblique tip and an eye in a flange at the other end, were originally designed for percutaneous, closed treatment of extracapsular hip fractures. Special sizes are available for the humerus and tibia. They are used in groups. (Courtesy of Howmedica, Rutherford, NJ.)
are designed to be used reamed or nonreamed. Some of these newer nails are made of titanium alloys. Titanium nails drive more easily due to their flexibility and are stronger than stainless-steel nails.

LOCKING NAILS
Since 1988, when the first edition of this book was published, locking intramedullary nails have gained wide acceptance and have revolutionized fracture care. The Grosse-Kempf (Howmedica Rutherford, NJ) (57) and Klemm (no longer manufactured) (60) nails were the first generation of locking nails. Many new second-generation designs are available, and they address a wide range of problems in the femur, tibia, and humerus. Although available, locking nails for the forearm have not yet gained wide use.

Locking nails have made single nonlocking nails obsolete. The only advantages of nonlocking single nails are their simplicity and low cost.

Nearly every fracture combination in the femur can be addressed by percutaneous fixation techniques. Except for the Brooker-Wills nail (Biomet, Inc., Warsaw, IN) (Fig. 11.69) with its flanges, and the expandable tip of the Seidel nail (Howmedica, Rutherford, NJ), which is used exclusively for the humerus, all current designs use two or more distal transverse cross-locking screws, as in the Alta intramedullary rod (Howmedica, Rutherford, NJ) (Fig. 11.65B) (110). Proximal fixation includes inclined screws, as in the Grosse-Kempf nail (Fig. 11.65A); two transverse screws, as in the Alta (Fig. 11.65B); and specialized screws through the nail designed to secure fixation in the femoral head, as in the Russell-Taylor nail (Smith Nephew Richards, Memphis, TN) or the Alta CFX nail (Howmedica, Rutherford, NJ) (Fig. 11.70). The Alta nail is designed to have its two proximal cross-locking screws located just distal and proximal to the lesser trochanter when the top of the nail is flush with the cortex at its entry hole. This permits the surgeon to set the nail more proximally to secure fixation in the femoral neck without having the nail protrude above the tip of the greater trochanter (Fig. 11.71). This allows fixation of subtrochanteric fractures that include even the lesser trochanter.

Figure 11.69. Brooker-Wills nail fixing a fracture of the femur, AP roentgenogram. This nail is a variation of the Küntscher nail with flanges deployed through slots in the tip of the nail for distal stability. They are deployed internally, and it has an oblique cross-locking screw proximally. With the advent of more advanced cross-locking designs, this nail has disappeared from the marketplace. (Courtesy of Andrew Brooker, M.D., Baltimore, MD.)
Figure 11.70. Russell-Taylor reconstruction nail, a third-generation nail. Proximal locking into the femoral head makes it useful for hip fractures. (Courtesy of Howmedica, Rutherford, NJ.)
The Alta nail, along with some other systems, offers the unique advantage that the surgeon can combine hip fixation systems with the intramedullary nail for the fixation of intertrochanteric–subtrochanteric fractures, and concomitant ipsilateral fractures of the femoral neck and femoral shaft (Fig. 11.72).

**Figure 11.71.** A: Subtrochanteric fracture of the femur at the level of the lesser trochanter. B: Fracture fixed with an Alta intramedullary nail and two transverse cross-locking screws inserted across the femoral neck. Distal cross-locking screws were used as well.

**Figure 11.72.** A: Alta intramedullary nail with rod connector and hip screw used to fix concomitant ipsilateral femoral neck and shaft fractures, as well as subtrochanteric fractures of the femur. B: Alta rod connector in a plastic femur, combined with a hip bolt for fixation in the femoral head. C: Fracture of the femoral neck fixed with an Alta bolt. A rod connector and an intramedullary nail are used to fix an ipsilateral concomitant femoral shaft fracture. (Courtesy of Howmedica, Rutherford, NJ.)
SPECIALIZED NAILS

Since the initiation of early locking nail designs, many specialized nails for particular problems have been developed based on the locking principle. The Zickel nail (117,118) for subtrochanteric and supracondylar fractures of the femur is now obsolete because it is not a fully cross-locked nail, and the Sage nail (91) for fractures of the radius and ulna has been replaced by plates, again because cross locking is not available.

An early specialized nail was the gamma nail (Howmedica, Rutherford, NJ) (Fig. 11.73), developed initially in a short design for fixation of intertrochanteric and some intersubtrochanteric fractures. This nail has been extremely successful in Europe but has not gained much popularity in North America. When it was introduced, the principle of overreaming and sliding the nail in by hand was not appreciated by early users in North America and this led to an unacceptable incidence of additional subtrochanteric fractures of the femur. The gamma nail is now available in a long device that functions like most reconstruction nails, except that a single locking screw is used in the femoral head and neck. Nearly every manufacturer now offers a third-generation, so-called reconstruction nail; in this system, different types of screws are inserted through the reinforced larger proximal section of the nail up into the head neck fragment of the femur. When combined with distal cross-locking screws, these devices enable the surgeon to stabilize single or combination fractures from the femoral neck to the supracondylar area of the femur. Similar design concepts have now been applied to the humerus as well.
**INDICATIONS**

**CLOSED FRACTURES**

The use of intramedullary nails is most appropriate in patients with displaced, closed fractures of the lower extremity, who have unstable fracture patterns and in whom early weight-bearing and rehabilitation is advantageous. Fracture patterns (Fig. 11.74) are important to consider in making therapeutic decisions (21,22,26,113). Unless some type of supplemental external protection is used, simple oblique or spiral fractures are the only fractures that are nearly always stable after reamed or nonreamed intramedullary nailing without locking (Fig. 11.74A, Fig. 11.74B). The fracture configurations in Fig. 11.74C, Fig. 11.74D, Fig. 11.74E, Fig. 11.74F and Fig. 11.74G generally remain unstable with the use of routine reamed or nonreamed nails, and interlocking nails are required. Noninterlocking nails must not be used in the latter group of fractures unless special precautions are taken to prevent shortening and malrotation. Protection for 6 to 12 weeks is often necessary, depending on the fracture configuration.

**Figure 11.73.** Gamma nail. This intramedullary device is designed for proximal intramedullary fixation of intertrochanteric and some subtrochanteric fractures. It is available in a long version as well.

**Figure 11.74.**

A: Midshaft transverse or short oblique fractures are stable and therefore ideal for closed intramedullary nailing. B: Midshaft fractures with short butterfly fragments are also stable if there is 50% or greater contact between the proximal and distal fragments. C: Midshaft fractures with large butterfly fragments and less than 50% contact are unstable after routine nailing. An interlocking nail in the static mode should be used. D: Segmental comminution requires
Even simple transverse fractures can easily malrotate. Fractures often have unseen cracks that can progress and lead to instability. I lock nearly all nails at both ends now. Even in transverse fractures, I prefer to distally lock the rod first, impact the fracture with the slap hammer driver, and then lock proximally. With such good bone contact, immediate weight-bearing is almost always possible.

The treatment of choice for most closed fractures of the femoral shaft in adults and older adolescents is closed intramedullary nailing (30,113). A review of the literature comparing closed intramedullary nailing to open intramedullary nailing, plate fixation, and cast-brace treatment confirms this view (110).

In the tibia, most closed fractures are best treated by nonoperative means, using a weight-bearing cast or cast-braces (see Chapter 24). Closed nailing is reserved for fractures that develop unacceptable malposition with routine closed treatment or are obviously unstable at the outset.

Indications for intramedullary nailing of the humerus are rare. Most of these fractures are nicely managed by closed technique. The few fractures that do require surgical intervention are usually best treated by plates and screws, but selected indications for reamed and nonreamed intramedullary nails are discussed in Chapter 15. In displaced fractures of the forearm, the best results in adults have been reported with plate fixation; indeed, the use of intramedullary nails has been associated with an increased incidence of nonunion and angulation (5). Locked forearm nails have not proven to be superior to plates.

**OPEN FRACTURES**

Intramedullary nailing of open fractures remains controversial. However, Brumback et al. (20) and Lhowe and Hansen (66) have shown that nailing of open fractures of the femur can be done with an acceptable complication rate, provided the benefits of the procedure outweigh the risks. Although Hansen et al. recommend immediate nailing of all open fractures of the femur, the infection rate may be lower if nailing is delayed in type IIIB open fractures. Immediate stabilization of all femur fractures is important for victims of multiple trauma to salvage life. Intramedullary nailing is the procedure of choice for most of these patients.

For isolated open fractures of the femoral shaft, perform a meticulous irrigation and
debridement, including thorough irrigation of the bone and medullary canal at the fracture site, and initiate appropriate intravenous therapy as described in detail in Chapter 12 on Open Fractures. In Gustilo grades 1, 2, and 3A fractures, I almost always carry out locked intramedullary nailing. Since the fracture site is open, nailing is simplified and the majority of these cases can be stabilized on a regular operating table

with the patient in the lateral decubitus position using an antegrade approach. I leave the traumatic wound open and perform delayed primary closure at approximately 5 days. It is important to protect the vascularity of the femur in open fractures, so I use gentle, minimal reaming and usually an 11 mm nail. In large men, this nail can often be implanted without reaming. Although the risk of infection is low, this makes recovery more likely if infection does ensue, as the diaphysis will be better vascularized and less likely to become a sequestrum. In isolated high-grade 3B or C open fractures of the femur, which are exceedingly rare, I also consider immediate intramedullary nailing using a nonreamed or minimally reamed small nail, as long as the wound is not highly contaminated and the delay from time of injury to surgery is not more than 6 hours. Brumback et al. (20) had an exceedingly low rate of infection after immediate-reamed nailing of open fractures of the femur and encountered an unacceptable infection rate only when debridement and nailing was delayed for more than 24 hours. In the presence of exceedingly severe soft-tissue wounds, high levels of contamination, and delay in treatment, my treatment of choice is external fixation with conversion to reamed intramedullary nailing when the soft tissues have recovered, the wounds are closed, and there is no evidence of infection. The procedure for conversion from external fixation to nailing is described above, in the section on external fixation.

My approach to open fractures of the tibia is similar to that of the femur. Early studies comparing nonreamed intramedullary fixation with Lottes nails with external fixation showed comparable results (67,104). As a result, when locking nails became available, nonreamed locking nails quickly became the stabilization method of choice for the vast majority of open fractures of the tibia as reflected in discussion in Chapter 24 (note the results listed in Table 24.7). External fixation is reserved for those fractures that are unsuitable for nailing because of their configuration, or in those that are highly contaminated and irrigation and debridement has been excessively delayed, as discussed for the femur. Because of their small size, nonreamed nails have experienced significant failure rates, with fracture of screws reported up to 30%, and delayed and nonunion rates reported up to 20%; therefore, some centers have studied minimally reamed and fully reamed nails for the fixation of open fractures. This is discussed in detail in Chapter 24. Recent reports, particularly those from Court-Brown et al. (31), have shown complication rates in reamed nailing of open fractures to be comparable to those with nonreamed nails with improved union rates, less hardware breakage, and fewer malunions.

My approach to this issue is to now always try to place 10-mm-diameter titanium nails, which permits the use of the strongest 5-mm-diameter cross-locking screws (Fig. 11.75). With this device, fixation is secure and hardware failure exceedingly rare. A nail this size can be passed unreamed in about 40% of men, and with the passage of only one or two reamers in the remainder. Women require somewhat more reaming, so in the smallest I will
I have nearly abandoned nailing of the humerus, because if the fracture is open I much prefer plate and screw fixation as it better preserves the blood supply to the diaphysis, and injury to the rotator cuff is avoided.

**TECHNICAL CONSIDERATIONS**

**TIMING**

When using a closed technique to treat closed fractures, nailing can be done as soon as practical after injury. However, evidence suggests that if nailing is done with an open technique, a delay in nailing of 7 to 10 days may increase the union rate by taking advantage of the secondary injury phenomenon (25,28,99).

**ENTRY SITES**

With reamed rods, which are generally fairly rigid, the entry site must be directly above the intramedullary canal. Eccentric entry sites, particularly in the femur and tibia, can result in incarceration of the nail or comminution. At the proximal end of the femur, the entry site for reamed nails is in the thin cortex at the base of the greater trochanter, at the site of its junction with the superior aspect of the femoral neck (see Chapter 20) (Fig. 11.76). The entry site on the femur for retrograde nailing is centralized on the intramedullary canal on both AP and lateral views with the fluoroscope and distally in the intercondylar notch just posterior to the articular cartilage and anterior to the origin of the anterior cruciate ligament (see Chapter 20).
For entry into the femur, most surgeons now use a guide pin and cannulated reamer rather than an awl; this offers better control and facilitates the use of the fluoroscope to identify the proper entry site. In the tibia, the most direct route is to split the patellar tendon and enter the bone just proximal to the tibial tubercle. To avoid injury to the patellar tendon, some surgeons enter just medial or lateral to it.

Because of the obvious advantages of not splitting the patellar tendon, I used the medial parapatellar approach for a year or so at the University of California, Davis, Medical Center. Although nailing can be successfully carried out through this portal, I found that in the hands of less experienced surgeons it was difficult to obtain an entry site directly over the medullary canal, resulting in unacceptable angulation of the nail relative to the longitudinal axis of the medullary canal. In addition, I have not seen any significant long-term consequences from splitting the patellar tendon. For that reason, I now always split the patellar tendon. In the tibia, flexible nails such as the Ender are usually inserted on the flares of the metaphysis of the proximal tibia. This technique is discussed in more detail in Chapter 24.

In the humerus, reamed nails are introduced at the proximal end. To avoid injury to the rotator cuff, try to locate the entry site just distal to the insertion of the rotator cuff tendons on the lateral aspect of the humerus, just below the prominence of the greater tuberosity, if the nail design permits. Many nails must be inserted through the cuff. Unfortunately, these result in residual shoulder symptoms in many patients. The entry sites for the radius and ulna are discussed in Chapter 16.

For nonreamed, flexible nails, an eccentric entry site is usually used to take advantage of three-point fixation of the curved nail within the medullary canal. Generally, these nails are inserted distally through the supracondylar flares of the long bones. Because of the limited space in the epicondyles of the humerus, the entry site advised for Ender nails in the humerus is centrally posterior, just proximal to the olecranon fossa. At entry sites, avoid impingement on neurovascular structures; to avoid stress risers, do not make the holes too

\[ Figure 11.76. \text{Entry point for the medullary nail. A: This axial view, seen from the femoral head looking distally, represents the position of the femur in relation to the surgeon. Insert the guide pin at the base of the greater trochanter at its junction with the femoral neck in the region of the insertion of the obturator internus. Note that this entry point is neither on the femoral neck nor on the tip of the trochanter. Drive the pin into the medullary canal with a mallet. B: This direct view of the top of the femur better illustrates the proper location for the entry hole, which is directly above the medullary canal. (From Chapman MW. Closed Intramedullary Nailing of Femoral-Shaft Fractures: Technique and Rationale. Contemp Orthop 1982;4:213, with permission.)} \]
The nails should not be prominent enough to produce bursae or skin problems.

**FRACTURE REDUCTION**

Generally, the earlier a fracture is nailed, the easier is reduction of the fracture. Shortly after injury, the hydraulic effects of edema fluid can cause shortening and rigidity of the limb segment, which may make fracture reduction extremely difficult. If nailing is not done before this degree of edema occurs, gentle traction may be necessary to regain length and alignment gradually as the edema subsides. If intramedullary nailing is absolutely indicated, it may even be advantageous to distract the fracture slightly before surgery to facilitate reduction. With maintenance of length and early nailing, reduction is usually easy.

In fractures of the femur, reduction is most easily achieved by placing the distal fragment in a neutral position, avoiding tightness of the iliotibial band, which could otherwise result in shortening and a fixed valgus deformity (Fig. 11.77). The neutral position is achieved with 15° to 20° of hip flexion, and with the distal fragment level with the floor in the lateral decubitus position. It can also be achieved in the supine position. The proximal fragment is then aligned with the distal one by manipulating it with an intramedullary nail placed temporarily in the proximal fragment (Fig. 11.78). The Alta system has a fracture manipulation tool that enhances fracture reduction and guide-pin placement, and it can also be used to measure nail length (Fig. 11.79).

**Figure 11.77.** A: In the adducted position, the iliotibial band is tight, shortening the fracture and causing a fixed valgus deformity. B: A “neutral” position relaxes the iliotibial band, facilitating reduction. (From Chapman MW. Closed Intramedullary Nailing of Femoral-Shaft Fractures: Technique and Rationale. *Contemp Orthop* 1982;4:213, with permission.)

**Figure 11.78.** In manipulating the proximal fragment, lateral pressure at point A brings the distal end of the proximal fragment to point B. Downward pressure at point C then moves the proximal fragment into alignment with the distal fragment. Careful, methodical, and thoughtful technique usually permits quick passage of the guide pin. (Illustration by Beverly A. Kessler, courtesy of LTI Medica, New Scotland, NY, and the Upjohn Co., Kalamazoo, MI, copyright LTI.)
When the supine position is used for femoral nailing, the torso may obstruct manipulation of the proximal fragment. Direct manipulation of the fracture site is often necessary. To avoid radiation exposure of the surgeon, use manipulation devices such as the crutch and strap advocated by Küntscher. Use the fracture table for fractures of the femur and tibia to facilitate reduction. As the tibia is subcutaneous, direct manual manipulation results in reduction in most cases.

In the upper extremity, fracture tables are rarely used. Reduction is achieved by a combination of manipulation of the proximal fragment with the nail and direct manual manipulation of the distal fragment and fracture site.

In open nailing, the key to reduction is to angulate the fracture. Approximate the corners of the cortices of the proximal and distal fragments at an acute angle and then straighten the fracture into appropriate alignment. If nonreamed nails are used, this manipulation is facilitated by placing the nail in the proximal fragment before manipulation. In reamed nailing, use an incision just large enough to achieve manipulation; after the reaming guide pin is placed, close the wound and proceed as for closed nailing. These techniques are described in more detail in the chapters devoted to fractures of each long bone.

**REAMING**

Reamers must be sharp, and the surgeon must consider the relationship between the size of the reamers and the nail. A 12 mm reamer is not necessarily equal in diameter to a 12 mm nail. Because flexible reamers follow a curvilinear pathway, overreaming is usually
necessary for most nails. Most nails require overreaming from 0.5 to 2 mm over the size of the nail, depending on the type of nail, the configuration of the fracture, and the canal of the bone.

**Reaming Technique for the Femur, Tibia, and Humerus**

- Insert a ball-tipped reaming guide pin across the fracture to the subchondral bone in the distal fragment.

- Begin with an end-cutting reamer, generally 8.5 to 9.0 mm in diameter. To avoid overheating and excessive pressure in the intramedullary canal, push the reamer slowly.

- Pay attention to the sound and speed of the reamer. Slowing of the reamer and intermittent catching are signs of impending jamming. In this situation, maintain full power, withdraw the reamer, clean it, and then readvance.

- When substantial cortical bone is being reamed, clean the reamer frequently to maintain effective cutting action. On the first pass of the reamer past the fracture site, visualize it on the fluoroscope to ensure that reaming is progressing appropriately; thereafter, it is not usually necessary to visualize the reamer.

- To avoid eccentric reaming and to allow the reamer head to pass the fracture site, an assistant may need to manipulate the fracture site gently.

- On withdrawal of the reamer, have an assistant hold a surgical towel or pad on the end of the guide pin to prevent its withdrawal along with the reamer. Driving the guide pin into the solid cancellous bone near the subchondral plate helps to stabilize the pin. Avoid grasping the guide pin with a bare surgical glove, as sudden turning of the guide pin will wrap up and rupture the glove.

- On withdrawal, the reamer will occasionally “hang up” at the fracture site or at the entrance to the bone because of the slight shoulder in the design of some reamer heads. Overcome this by advancing the reamer with full power, then retract it vigorously. If this is unsuccessful, try pulling the reamer eccentrically with an Army/Navy retractor while the power is on.

- It is safest to ream progressively in 0.5 mm increments. If the canal is large, after passing the end-cutting reamer, progress in 1 mm increments until firm contact of the reamer with cortical bone is established. Thereafter, progress in 0.5 mm increments.

- In general, avoid overreaming of the canal by more than 2 mm, as excessive thinning of the cortex may result in comminution during the drive of the nail. The exception is in reconstructive procedures and in young patients who have small canals, where considerable reaming may be required to accommodate a nail of adequate size.

- Occasionally, the entry hole for the nail, particularly in femoral nailing, is eccentric and off-line in relation to the canal. Correct this with the last reamer by pulling it
eccentrically in the direction of the central axis of the canal with an Army/Navy retractor while reaming the entry hole. This will produce an oval hole that will permit proper entry of the nail.

- If a reamer breaks or jams, remove it by pulling it out with the ball-tipped guide pin. Reamers must be powered by high-torque, low-rpm power sources designed specifically for intramedullary reaming.

- Avoid excessive pressurization of the canal by using reamers with large open cutting flutes and small-diameter shafts. Use a vent hole in the distal femur when indicated, and advance the reamers slowly using the highest rate of revolution provided by the power reamer.

**NAIL SIZE**

Obtain preoperative radiographs of the fractured long bone, including the proximal and distal joints. These help to rule out irregularities in the bone that might preclude nailing, and they also aid in the selection of an appropriately sized nail. If a full complement of intramedullary nails is available, it is usually unnecessary to measure patients for nail size before surgery unless they are of unusual stature. If there is any question, obtain AP and lateral radiographs of the opposite normal limb at a tube-distance of 1 m. Tape a nail of the appropriate size to the side of the limb for reference, or a radiographic ruler can be used; alternatively, a Küntscher measuring device—the ossimeter—may be used to measure length and width (Fig. 11.80). The ossimeter has two scales, one of which takes into account the magnification caused by the x-ray at a 1-meter tube distance. In most cases, a nail reaching to within 1–2 cm of the subchondral bone distally is indicated. In reamed nailing, the width of nail is better determined by the feel of the reamers than by radiographic measurements, although the approximate size to be used can be determined from preoperative radiographs. Diameter is critical in nonreamed nails, especially when a snug fit is anticipated. The radiograph is helpful in determining nail size before surgery, but, again, the feel of the nail as it is driven is most important.

**Figure 11.80.** A Küntscher ossimeter is a Plexiglas measuring device used to measure canal diameter and bone length from roentgenograms taken at a 1 m tube distance. A “real” scale and a special exploded scale (to allow for radiographic magnification) are available.
In comminuted fractures, it may be difficult to determine the proper nail length. A radiograph of the opposite normal bone with an appropriate-size nail taped to the extremity is quite helpful.

**INTERLOCKING NAILS**

Numerous designs of interlocking nails for the femur, tibia, and humerus and forearm are now available. The most common types of interlocking nails use transverse screws distally and oblique, or transverse screws proximally (Fig. 11.70, Fig. 11.71, Fig. 11.72, Fig. 11.73, Fig. 11.75, and Fig. 11.77). The guides for proximal cross locking are effective. Never subject nails to extremely hard driving, as distortion of the proximal end of the nail may interfere with both proximal and distal cross locking. Difficulties in passing the proximal cross-locking screw are almost always due to distortion of the proximal end of the rod or a loose connection between the nail and the guide. Before driving the rod, check all connections of the driver and guide.

**SURGICAL TECHNIQUES**

**CROSS LOCKING**

- To perform proximal cross locking, lock the proximal screw guide securely into place. Use the drill sleeve and an appropriate drill point for drilling. If the drill point contacts the rod, immediately withdraw it to avoid breakage.

- After drilling, measure the screw length with the depth gauge. Often this requires fluoroscopy, as it is difficult to feel the opposite cortex with the depth gauge. If the bone in the region where the cross-locking screws are being inserted is nearly round, then screw lengths can be determined by measuring directly on the fluoroscope monitor. The diameter of the rod is known (e.g., 12 mm). Have a nonsterile assistant or nurse mark the width of the rod on a piece of paper placed on the monitor screen and then use that as a reference to measure the width of the bone at the cross-locking hole. This is quick, easy, and accurate within 2 mm or so. It is not reliable when locking on a sloping surface such as the proximal tibia.

- Insert the screw, taking care to avoid cross threading the rod in threaded designs. The heads of most cross screws are quite prominent. Insert them to bring the top of the screw head flush with the bone of the greater trochanter to avoid trochanteric bursitis and a snapping iliotibial band, and prominent screw heads in other locations.

Guiding devices for distal cross locking do not work as well as those for proximal cross locking due to the flexibility of these long guides and distortion of the nail. The Alta system offers a rod-mounted distal cross-locking guide for the femoral, tibial, and humerus nails. The fluted design of the Alta nails minimizes nail distortion in rotation and varus and
valgus. The rod will bend in the anteroposterior plane, and this is adjusted for by the guide. It can be used with percutaneous technique, minimizing exposure to x-rays (Fig. 11.81).

Figure 11.81. Alta cross-locking guide for the femur. The guide mounts on the driver for the nail and is used for proximal and distal cross locking. The guide is radiolucent and has a system that facilitates percutaneous screw insertion with minimal use of x-rays. (Courtesy of Howmedica, Rutherford, NJ.)

Other manufacturers offer guides, some of which are based on a stabilizer probe placed at right angles to the cross-locking screws, which must be inserted down to articulate with the rod through a separate stab wound and hole drilled in the femur. These have met with mixed success. Laser light guides that mount on the C-arm head are used to facilitate free-hand targeting but are not in wide use as they do not eliminate the need to use x-ray. Guides using detection of a magnetic field can eliminate the need for x-ray except to verify screw position and length. They are just now in clinical trials.

FREE-HAND TARGETING
Free-hand methods for placing distal cross screws work well with all current designs.

- Position the heads of the C-arm fluoroscope for a lateral view of the distal end of the rod. Provide maximal clearance between the lateral side of the limb and the head of the C-arm. Align the C-arm with the first of the two distal cross holes. The cross hole to be targeted must be located directly in the center of the fluoroscope screen, must be perfectly superimposed, and must be round (Fig. 11.82). Achieving this alignment can be difficult. It may save time for the surgeon to break scrub to align the fluoroscope head while the radiology technician operates the controls of the C-arm. It saves considerable operating time if all controls on the C-arm are loosened and if the head is moved into position under direct fluoroscopy. Spot images can also be used but are much more time-consuming.

Figure 11.82. Lateral fluoroscopic view of the distal screws in an intramedullary nail. Notice that the hole, which is to be cross locked, is in the center of the screen and is perfectly superimposed.
Use a long, very sharp 1/8-inch (0.3 mm) Steinmann pin or a sharp drill point mounted on a radiolucent targeting handle, or held in a Kocher clamp to pinpoint the area of penetration of the bone and to avoid exposing the surgeon’s hands to the central beam of the fluoroscope. Bring the tip of the pin or drill point into the fluoroscope image, placing it on the skin directly over the screw-hole image. Mark the location for the skin incision.

- Make a 1 cm longitudinal incision directly over the screw hole down to bone. Insert the pin percutaneously to the cortex of the bone. Again, bring the tip of the pin into the fluoroscopic image at an angle to the fluoroscope beam and locate the tip of the pin directly in the middle of the screw hole (Fig. 11.83). Once located, carefully tip the pin to place it vertical to the cortex and directly in line with the fluoroscope head in all planes.

- Maintaining this alignment, mallet the pin into the cortex. It is often possible to insert the pin directly into the near hole on the rod.

- Once this hole is made, insert the appropriate-size drill point and, while maintaining
alignment with the fluoroscope head, drill the hole through the rod and the opposite cortex.

- Remove the power source, leaving the drill point in place. Verify with the C-arm that the drill point is directly in the center of the hole. Verify its position on the AP view. If you plan to insert two screws, leave the first drill point in place as it is a useful guide to the proper drilling angle for the second hole. Insert the second drill point with the same technique. Some systems have a hand-held guide that can be slipped over the first drill point to provide guidance for the second hole. Repeat the procedure just described.

- Now insert the appropriate-size screw. Once the initial pin or drill is through the rod and bone, I prefer to place a drill sleeve over the pin and then do subsequent drilling and screw insertion through the guide as this avoids getting lost in the soft tissues. With this technique, radiation exposure is minimized and only 5 minutes or so are needed to insert each screw.

Partially radiolucent power units that use a gunsight principle for targeting are available but are not widely used, as the drill points tend to “walk” on the cortex, and the power units are large and cumbersome.

**POSTOPERATIVE CARE**

The postoperative regimen used depends on the bone nailed, the quality of the bone, the stability of the fracture, and whether an interlocking nail has been used. If a noninterlocking nail has been used, the patient must be protected against shortening, angulation, and malrotation until early bone union has occurred. Because interlocking nails are used in the vast majority of cases, this discussion will be focused on locked nails.

In the femur, if the fracture pattern is stable and there is good bone contact over at least a 50% diameter of the cortex with an adequate-size nail and cross screws for the patient, patients can be encouraged to bear weight as tolerated using crutches or a walker. In my experience, the average patient will not attain full weight bearing before 6 weeks. During this period, the supporting musculature is quite weak and quadriceps control is poor; therefore, the patient has little control of the knee. Begin isometric exercises, followed by progressive resistance exercises, as soon as practical to reeducate the quadriceps and hamstring and other muscles. In the meantime, use a knee immobilizer to protect the knee. This can be discontinued when the patient regains good quadriceps control. In unstable fracture patterns, particularly where there is extensive comminution or lack of good bone contact between the major proximal and distal fragments, limit weight bearing to the weight of the leg until periosteal callus is seen bridging the fracture site on two views. At that point, weight bearing can be progressed as the fracture consolidates.

This same philosophy can be applied to the tibia; however, it is usually easier because the patients normally have good control over their knee. A patellar-tendon-bearing brace or similar protective orthosis is often useful, particularly in unstable fractures of the tibia.
In the humerus, external protection is usually unnecessary and the patient can begin immediate gentle range-of-motion exercises of the shoulder and elbow. Resistive muscle rehabilitation can usually begin as soon as bridging callus is seen, or earlier in stable patterns.

**PITFALLS AND COMPLICATIONS**

**MALPOSITION**

Although malposition of the fracture with subsequent malunion is unusual in intramedullary nailing, the surgeon must pay close attention to avoid it. In simple fracture patterns, establishing overall alignment of the bone and matching the fracture pattern usually results in good alignment, particularly since the bone automatically aligns itself on the rod. In simple fracture patterns, the most common problem of alignment is malrotation. Verify that the patient’s position has not shifted on the operating table prior to driving the rod, and be certain that rotation is comparable to the opposite uninjured extremity. In bilateral cases, align the first web space of the toes with the patella and the center line of the hip.

In complex comminuted fractures, particularly those extending into the metaphysis, angular malalignment of the distal or proximal metaphyseal fragments can occur, particularly since it is difficult to ascertain overall alignment on the fluoroscope. Inspect the limb clinically after insertion of the nail. It is occasionally prudent to get long AP and lateral radiographs immediately after insertion of the nail to be certain that proper alignment is present prior to placement of cross-locking screws. Once the nailing has been completed and the patient is lying in the supine position on the operating table, carefully examine the operated extremity. It is better to detect and correct malalignment now than to have to return the patient to the operating room or to allow malalignment to persist.

Another source of unexpected malalignment is when cross-locking screws appear to have gone through the nail on an AP view, but have actually missed the nail. Careful examination with the fluoroscope after completion of insertion of each screw is essential to be certain that the screw has in fact passed through both the bone and the locking holes in the nail. Take final plain films in the operating room to confirm the fluoroscopic visualization.

**DELAYED UNION**

Delayed union is most common in fractures of the tibia due to their increased severity. Delayed union and nonunion in the femur and humerus is unusual with intramedullary nailing because of the copious blood supply available from the surrounding muscular envelope. Other than the deleterious effects of the initial trauma, the most common cause of delayed or nonunion is distraction in the operative site. Brumback et al. have shown that dynamization of locked nails or removal of cross-locking screws before nail removal is unnecessary to achieve union (22). On the other hand, where the fracture pattern is stable and union is delayed (no evident callus bridging the fracture site by 12 weeks after nailing), dynamization may sometimes be indicated. For dynamization to be
effective, it is necessary to remove screws from the end of the nail farthest from the fracture site. It is important that, when the fracture site impacts with weight bearing, it becomes rotationally stable. Dynamization of a straight transverse fracture may lead to increased rotational instability and progression to nonunion.

NONUNION
The incidence of nonunion after closed intramedullary nailing of fractures of the femur is less than 1% to 2%, and only slightly higher in the tibia. The risk of nonunion can be minimized by utilizing closed techniques, and by ensuring good bone contact, preferably impaction, and stable cross locking with nails of sufficient size. If nonunion occurs, most cases are responsive to exchange nailing. Use closed-technique reaming to a larger nail and then provide compression across the fracture site with a compression device and lock the nail in compression. Of course, this is not applicable to fracture patterns that are axially unstable, where open bone grafting may be needed. This is discussed in detail in Chapter 26, Chapter 30, and Chapter 31.

NEUROLOGIC INJURY
In nailing of fractures of the humerus, the primary nerve at risk is the radial nerve. Although closed nailing techniques have been advocated for the humerus and used successfully, I have seen one radial nerve transected by an intramedullary nail or reamers using closed technique. For that reason, unless there are special circumstances precluding open nailing, I prefer to expose the fracture site to ensure that the radial nerve is not in danger, and then to perform nailing using open technique.

In the femur, the most common palsy is that of the pudendal nerve, which is usually due to inadequate padding or use of too small a perineal post, plus excessive traction for a prolonged period of time. If femur fractures are nailed early, within 24 hours, strong traction is rarely required. If traction is required to reduce a transverse fracture, apply it only long enough to reduce the fracture, and then release. Proper technique should prevent the vast majority of pudendal nerve palsies. Fortunately, nearly all recover without residual effects.

Paresis of the sciatic nerve or its components is usually due to excessive traction with the hip in a flexed position and the knee straight. For that reason, I always keep the knee flexed about 45°, and more if possible, during closed intramedullary nailing of the femur on a fracture table. The methods described above to avoid pudendal palsy are also applicable to avoid sciatic nerve palsy. Direct surgical injury to the nerve is also possible. The exposure used for closed intramedullary nailing is usually not large enough to allow formal exploration of the sciatic nerve, but look for the nerve in the surgical field. In small women with dysplasia of the hip, and in some Asians, the sciatic nerve rests very close to the greater trochanter when the hip is flexed 15° to 20° for nailing.

Transient paresis of the lateral femoral cutaneous nerve can also occur due to pressure from the traction post on the fracture table. To avoid this, use a well-padded post of adequate size and avoid excessive traction.

In closed nailing of the tibia, the nerve at risk is the common peroneal. Paresis can be
caused by placing the popliteal bar against the common perineal nerve and then applying excessive traction for prolonged periods of time. To avoid problems, use a thigh bolster that is at least 4 in. in diameter and well padded. Place it under the distal thigh rather than in the popliteal fascia. The region of the common perineal nerve near the head of the fibula should always be free of impingement.

Fortunately, most peripheral nerve palsies secondary to intramedullary nailing are neuropraxias, which recover nicely within a reasonably short period of time.

G. PRINCIPLES OF HARDWARE REMOVAL

In adults, I do not feel that routine removal of plates, screws, wires, or intramedullary nails is indicated. The primary indication for removal is pain due to the implants, or a request by the patient for removal for reasons important to her. Another possible indication is a plate or screw on the diaphysis of a long bone, which is a stress riser in a patient involved in sports or in an occupation carrying increased risk for fracture, or increased risk for a fracture of worse severity because of the presence of the hardware.

In children, unless removal poses unacceptable morbidity, we advise routine removal of implants, particularly if they are composed of titanium. The rational is that implants in children tend to become very tightly integrated to bone and are commonly overgrown by bone, making subsequent removal exceedingly difficult if not impossible. There do not appear to be any adverse effects of leaving current stainless-steel and titanium implants for up to 40 years. However, the long-term effects of leaving these implants in place for 60–70 or more years is not known; therefore, removal in children seems advisable.

In addition, high-performance athletes may complain that their limb feels not as lively as before they received the implant. This is usually caused by stiffening of the bone segment from the presence of the implant. Removal of the implant is usually necessary for the bone to regain its normal flexibility.

SURGICAL TECHNIQUES

REMOVAL OF PLATES AND SCREWS

Almost always, implants can be removed through the original surgical incision. To obtain a nice scar, unless contraindicated, I usually excise the old wound and use plastic closure techniques to ensure good cosmesis. Superficial cutaneous nerves and other structures are more at risk in hardware removal than at the time of initial surgery, as they are frequently bound down in scar. Look for these to avoid injury. Occasionally, the pain associated with hardware is due to nerve entrapment or a neuroma. Treat this at the same time.

- In removing plates and screws, remove only the bone covering the screw head or plate that interferes with its removal.
- It is easy to strip screws, making their removal very difficult. Be certain that the head
of the screw is completely cleaned of bone and that a good-quality screwdriver without a worn tip is firmly engaged into the screw head.

- Taking a slight turn in the direction of tightening often breaks any bone adherent to the screw and makes turning the screw outward easier. If the screw breaks or if broken screws are encountered, there are screw removal sets available from several manufacturers. These usually require overdrilling of the screw. On the other hand, in adults, a broken screw tip in the opposite cortex may not be in a position that will bother the patient and can be left in place.

- When removing plates and screws, avoid creating a stress riser in the bone that might lead to refracture. If the plate is totally uncovered and does not easily lift off the bone, place an osteotome beneath the plate and drive along the underside of the plate parallel to the bone and plate. This usually results in fairly easy removal. The sharp instruments used for hardware removal should be from a special set reserved for that purpose, to avoid damaging high-quality instruments used for initial surgery.

- Once the screws and plates have been removed, resist the temptation to curet the screw holes. This is not necessary for healing and simply makes the screw hole wider, thus increasing the risk of refracture.

- In most cases, the plate will be surrounded by a ridge of bone that has grown up around the edges of the plate. Never remove these ridges, as they serve to reinforce the bone in the early remodeling phase after hardware removal. Nubbins of bone sticking up from the screw holes can be removed if necessary for patient comfort.

Many of the considerations discussed here are not applicable to nails, as they are removed utilizing closed percutaneous techniques, and a significant stress riser is not left in the bone. The major challenge in removing intramedullary nails, particularly in the femur, is identifying the end of the nail and inserting the removal instruments. This is particularly a problem in the femur, where a bone cap commonly forms over the proximal end of the nail. Good surgical exposure and use of a fluoroscope to locate the top and the longitudinal axis of the nail is very helpful. A fluoroscope should also always be used for removal of screws for the same reason. Most intramedullary nails are now provided with cap screws that prevent bone growth into the threads of the nail. I like to place a reaming guide pin down to the top of the nail when there is a bone cap on the nail: I then use a reamer to expose the top of the nail. It is then fairly easy to remove the cap screw, insert the rod remover, and extract the nail. Many intramedullary nailing systems have removal instrumentation that is different from that used to insert the nail. Be certain to follow the manufacturer’s recommendations and use the appropriate instrumentation.

**POSTOPERATIVE CARE**

In the case of intramedullary nails, as soon as the patient is comfortable, he or she can be weaned off crutches to bear full weight, assuming that the fracture is solidly healed and does not have a defect in it. Once full muscle rehabilitation has been achieved, patients can return to sports and occupational activities without limitations.
In the case of plates and screws, however, more caution needs to be taken because removal of the plate and screws leaves the bone in a weakened condition with holes that are stress risers. If the fixation device is confined to the metaphyseal or epiphyseal regions of the bone, then generally the same guidelines as applied to nails can be used. In the mid diaphysis, however, assuming that the fracture is solidly healed, patients can return to functional use of the limb as tolerated, but they must avoid any activity that would predispose them to fracture until the diaphysis remodels and the screw holes fill in. The timing on this depends on the bone, the age of the patient, and the particular fracture and implant involved.

The highest-risk situation is in the athlete competing in a contact sport. I recommend the following as a general protocol: Typically, the athlete sustains the fracture during the active season (let us assume the sport is football and the fracture occurred in October). If the fracture heals within the expected time and the callus is adequate to support stress, I permit the athlete to return to a general conditioning program, avoiding high-risk activities or contact sports, by 6–8 months after the initial injury. The football player could then engage in fall practice in August and return to competitive football in the fall, approximately 1 year after injury. If intramedullary nails are in place, no special precaution or protective device is necessary.

If the plates are on the upper extremity, then a protective brace is indicated. The athlete should recognize that if a second severe trauma occurs, a fracture at the end of the plates could result. If plates are in the lower extremity, on the mid diaphysis of the femur or tibia, I would not permit the athlete to play contact sports that season. When that season is over, the time would be opportune for the removal of the implant, as by then it would be approximately 18 months since the injury and the bone should be solidly healed. In the case of plates, I would preclude high-risk activity or contact sports for approximately 6 months after removal. Then the patient could gradually return to full-contact activities by approximately 9 months after implant removal, assuming that the appearance of bone is satisfactory on radiographs.

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