Hardware and Osteotomy Considerations

8

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This chapter was originally published in my book *Principles of Deformity Correction* in 2002. I was asked to publish this chapter for this new book of my colleagues from Istanbul University. Because of the limited page numbers and images, this time I had to extract some of the topics which are originally mentioned in this chapter. However, you will be able to find more information about extracted topics on related chapters all along the book, and you can also look for *Principles of Deformity Correction* in Chap. 11 (*Paley D*: *Principles of Deformity Correction*. Berlin: Springer-Verlag, 2002).

8.1 Choice of Hardware

The choice of hardware depends on several factors: patient age, level of osteotomy, number of osteotomies, type of osteotomy (percutaneous versus open), acute versus gradual correction, bone factors (diameter, patency of medullary canal, vascularity, etc.), soft tissue factors (coverage, vascularity, etc.), joint factors (stiffness, intra-articular hardware, irritation from hardware, etc.), and familiarity of the surgeon with the hardware and techniques of application. Availability of hardware may be the determining factor in developing countries and in situations in which cost is a key concern.

Most deformity corrections can be performed with various methods of fixation. The importance of the CORA method of planning is that the principles can be applied with most hardware systems. The biggest failings are associated not with the type of hardware chosen but rather with the way it is applied. Often, the osteotomy level and type of correction are determined by the limitations of the chosen hardware rather than the hardware's being chosen based on the level and type of correction.

8.2 Patient Age

With pediatric patients, size and physes must be taken into consideration. Bone diameter and length limit the size of the implants that can be used. Holes in the bone greater than one third of the diameter of the bone significantly weaken the bone and result in a high risk of fracture through the hole, either during fixation or after removal. Removal of internal fixation after healing is frequently recommended for children and young adults because of the theoretical risks of carcinogenesis, stress shielding, and stress risers as well as the difficulties of late removal and future surgery. Children also heal quickly, and the time for fixation is therefore short. Accordingly, external

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M. Çakmak et al. (eds.), *Basic Techniques for Extremity Reconstruction*,
https://doi.org/10.1007/978-3-319-45675-1_8

fixation may be preferable for children in many situations because the fixator is left in place for a limited period of time, and no hardware is retained. External fixation can easily avoid the physis and can even bridge across joints. The rapid healing ability of children often obviates the need for rigid fixation. In some cases, fixation may be accomplished with crossed K-wires and plaster. The presence of open physes contraindicates the use of intramedullary nailing (IMN) in most cases. The risk of avascular necrosis after femoral nailing through the piriformis fossa cautions against the use of IMN in adolescents with open physes [1].

8.3 Closing Wedge Osteotomy

Closing wedge osteotomy is perhaps the most common method of osteotomy because it produces excellent bone-to-bone contact and stability. Closing wedge osteotomies are most commonly stabilized using internal fixation, especially with screws and plates. Because bone must be removed, this osteotomy is usually performed open, under direct vision, rather than percutaneously. The most important step is to identify the closing wedge CORA to avoid creating secondary translation deformities. When the CORA is at the apex of the closing wedge (osteotomy rule 1), the bone is realigned without secondary translation deformity. If the CORA is proximal or distal to the osteotomy line, secondary translation will result if translation of the bone ends is not performed (osteotomy rule 3). Therefore, when the CORA is intentionally distant from the osteotomy, the bone ends should be angulated and translated according to osteotomy rule 2.

K-wires can be used as guides to mark the level and direction of the planned closing wedge osteotomy (Fig. 8.1). The K-wires should converge on the closing wedge CORA. They should also be in the true plane of angulation. The bone can be cut using a saw or an osteotome. It is preferable and easier to make each side of the osteotomy perpendicular to the long axis of each respective side of the long bone. To ensure that the correct amount of bone is resected, the angle

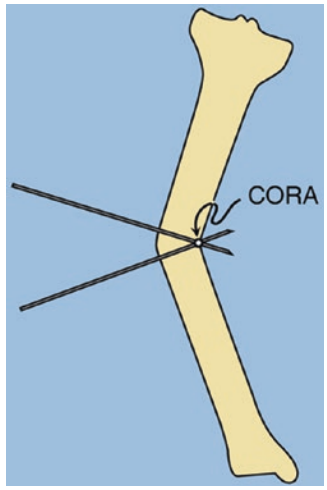

Fig. 8.1 To mark a closing wedge, two K-wires are driven perpendicular to each segment, proximal and distal to the osteotomy

between the K-wires is measured and should correspond to the magnitude of angulation. If osteotomy rule 1 is followed, the concave cortex is left intact and cracked at the time of the closure of the wedge. If the osteotomy line needs to be translated (osteotomy rule 2), the concave cortex needs to displace.

The bone can be cut freehand or by using a guide. The most common difficulty is preventing deformity in another plane. This occurs from cutting the two sides of the closing wedge in a nonparallel fashion. This will create an angular deformity in another plane to maintain bone contact. Alternatively, if correction is constrained to a plane different from that of the cut, the bone ends will not be in contact except at one point. Another common shortcoming of the closing wedge technique is accuracy. Despite preoperative planning, and even the use of templates or guides, inaccuracy can occur in making a closing wedge osteotomy because of the thickness of the osteotome or saw blade, templating error, and the amount of compression of the bone ends by the hardware [2, 8].

Templating can be performed by using metal wedges or by inserting Steinmann pins with an angle-measuring guide. When using an Ilizarov external fixation device, a saw guide can be constructed using metal plates (Fig. 8.2).

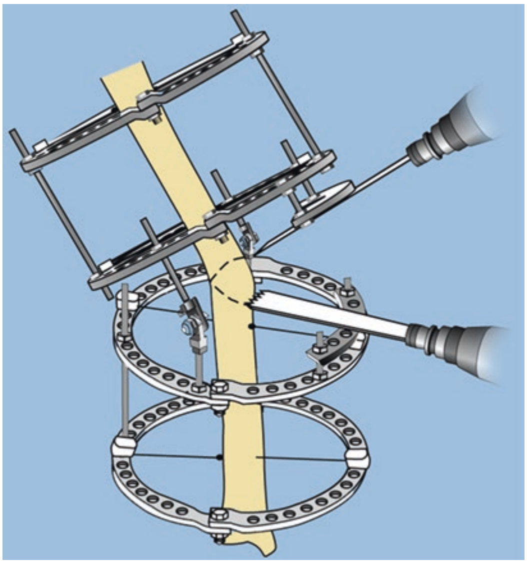

Fig. 8.2 The Ilizarov apparatus can be applied using a closing wedge hinge (hinge on the concave cortex). Because the rings on the other side of the hinge are perpendicular to their respective bone segments, the rings can be used as a saw guide. A plate is suspended from each of the middle rings, and the saw blade rests on the plate

The fixator is applied with the proximal rings parallel to the proximal part of the bone and the distal ring parallel to the distal part of the bone, with the hinge centered on the CORA. The plates are applied parallel to the proximal and distal rings to make the proximal and distal cuts of the closing wedge osteotomy.

The bone substance removed by closing wedge osteotomy can be morcelized and used as bone graft around the osteotomy site. Dissection around a closing wedge osteotomy can usually be performed with preservation of the periosteum. Limited soft tissue dissection is required proximally and distally on the convex side, with little if any dissection on the concave side.

When translation is required with closing wedge correction, additional soft tissue dissection is required to permit the bone ends to displace relative to each other. If the periosteum is freed up on the concave side, the bone ends will be able to shift without tearing the concave periosteum. The advantage of a bone and soft tissue hinge is lost in this situation, requiring increased stability from the internal or external fixation. The order of correction for acute closing wedge with translation is translation first and then angulation. If angulation is performed first, the soft tissue and bone hinge may lock, making it technically difficult to displace the bone ends. If translation is performed first, the bone ends are shifted when there is little bone contact and before there is any soft tissue tension. When a closing wedge technique is combined with translation, the width of the wedge resected can be reduced, creating a neutral wedge with translation (Fig. 8.3). The width of the wedge resection corresponds to the area of bone contact after the closing wedge is translated. With a neutral wedge correction with translation, the half wedge resected can be used to fill the space on the translated concave side. A closing wedge correction can also be performed, leaving the convex cortex as an instant hinge. If the concave cortex is left intact, the osteotomy can be stabilized with staples or a tension band wire.

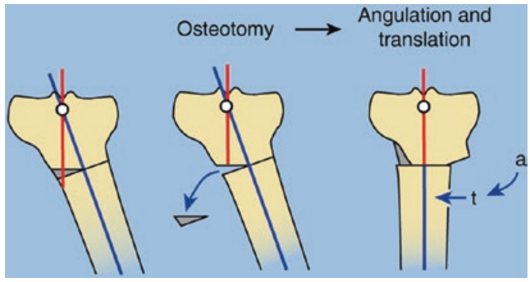

Fig. 8.3 When translation is planned, a hemiclosing wedge (neutral wedge) with translation may be preferable to a full width closing wedge. The wedge removed can be used as bone graft on the side of the bone that has the step due to translation. *a* angulation, *t* translation

8.4 Opening Wedge Osteotomy

With opening wedge osteotomy, as with closing wedge osteotomy, the appropriate CORA must be identified and marked. If the osteotomy is at the level of the CORA, the convex cortex acts as the ACA. The osteotomy is simpler because it is a single straight cut extending from the concave cortex toward the opening wedge CORA. The periosteum on the concave side can be elevated proximally and distally to prevent disruption at the time of opening wedge correction. This technique is more successful with small opening wedge corrections. Periosteal integrity on the concave side is difficult to preserve in most instances. In contrast, both the periosteum and the cortex can often be preserved on the convex side. Opening wedge osteotomies can be performed percutaneously or open. With the former method, there is minimal soft tissue stripping; therefore, despite the loss of bone contact, there is a strong propensity for healing, especially with children. When the osteotomy is performed open, it is preferable to minimize soft tissue dissection.

Opening wedge osteotomy is associated with the risk of bone healing problems because of the limited bone contact. Nonunion or a low cross-sectional area of union may result. To prevent this, bone grafting should be considered, especially in diaphyseal regions and in adults. Morcelled autogenous cancellous bone graft is preferred when internal or external fixation is used. Tricortical iliac crest or fibula is preferred if bone grafting is required to provide structural support. In the future, bone graft substitutes will play an important role, avoiding the need for bone grafting. Intramedullary "reamings" are another excellent source of bone graft. If IMN is used for fixation, the reamings will exit into the opening wedge defect if the opening wedge osteotomy is performed before reaming.

To reduce the loss of bone contact with opening wedge corrections, an a-t correction may be preferred. With the a-t method, one bone end is inserted into the medullary canal of the other bone end. There is less risk of bone healing problems. The a-t type of opening wedge osteotomy is chosen when the osteotomy is made at a level different from that of the CORA. If it is performed at the level of the CORA, a secondary translation deformity will result. The osteotomy may be intentionally chosen at a level different from that of the CORA to improve bone contact (Fig. 8.4). Other advantages include less stretch of soft tissues, no need for bone graft, increased stability, and amenability to either a percutaneous or open osteotomy technique. If a saw is used, care needs to be taken not to burn the bone ends.

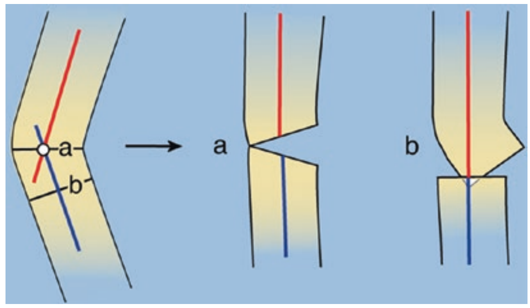

Fig. 8.4 To improve the bone contact at the opening wedge osteotomy site, the osteotomy can be made at a level different from that of the CORA, and the bone ends can be translated so that the corner of one segment is in the canal of the other segment

Opening wedge correction can be performed acutely or gradually, depending on the hardware used and the severity of the deformity. The larger the deformity is, the more stretch will result from an acute correction. Neurovascular structures are at the highest risk, especially if they are located on the convex side. The magnitude of angular deformity that can be corrected acutely when neurovascular structures are on the concave side is larger than when they are on the convex side (e.g., acute correction of proximal tibia vara is safer than acute correction of proximal tibia valga). Opening wedge correction stretches the soft tissues more than does closing wedge correction.

Gradual correction currently requires an external fixator; it is possible that in the future, gradual correction will be performed with innovative internal devices. Acute correction is amenable to both internal and external fixation. Gradual correction is more accurate than acute correction [3, 14]. This is because of the external fixator and not because of the method of correction. Acute correction can be as accurate, especially if it is performed with fixator assistance. Templating wedges are available to increase the accuracy of opening wedge corrections [11, 13].

8.5 a-t Osteotomy

The a-t osteotomy is performed either as a closing or opening wedge procedure, as described above. It is very useful and should be used at a level different from that of the CORA, following osteotomy rule 2. If it is performed at the level of the CORA, a secondary translation deformity will result.

8.6 Dome Osteotomy

The so-called dome osteotomy is not shaped like a dome at all but rather like an arch (a dome has a spherical surface, whereas an arch has a cylindrical surface). This cylindrical bone cut is corrected by rotating around the central axis of the cylinder. If the axis of the cylindrical bone cut is not matched to the CORA, a secondary translation deformity will result. If the axis of the cylindrical osteotomy and the CORA correspond, the correction will follow osteotomy rule 2, with no secondary translation of the axis lines but with angulation and translation of the bone ends. The dome osteotomy is an a-t osteotomy with better bone contact than that provided by the straight cut variant. It is much more difficult to produce a dome osteotomy than a straight cut. There are many ways to make dome osteotomies. Special curved saws and osteotomes are available for domes of a small radius, such as in the metatarsals. In larger bones, multiple drill holes are made in a circular pattern and connected with an osteotome. With the multiple drill hole method, any radius of curvature can be made. Although templates can be used for different radii, it is preferable to use a central pivot point to guide the drill holes, similar to the way a compass is used to draw concentric circles. If the central pivot point is matched to the CORA, the axis of the cylindrical cut is centered on the CORA. This is called *focal dome osteotomy*.

Dome osteotomies can be used to correct angulation around the axis of the cylindrical cut and translation parallel to the walls of the cylinder (Fig. 8.5). The dome cannot be used to correct axial rotation. This is one of the limiting factors of the dome osteotomy. There are two modifications to the dome osteotomy that can be made to allow it to correct angulation and rotation at the same time. The first is to incline the dome cut so that the axis of correction is also inclined. An inclined axis will correct both angulation and rotation. The other way is to make a spiral dome osteotomy. This allows the bone surfaces to conform to each other as angulation and rotation corrections occur together.

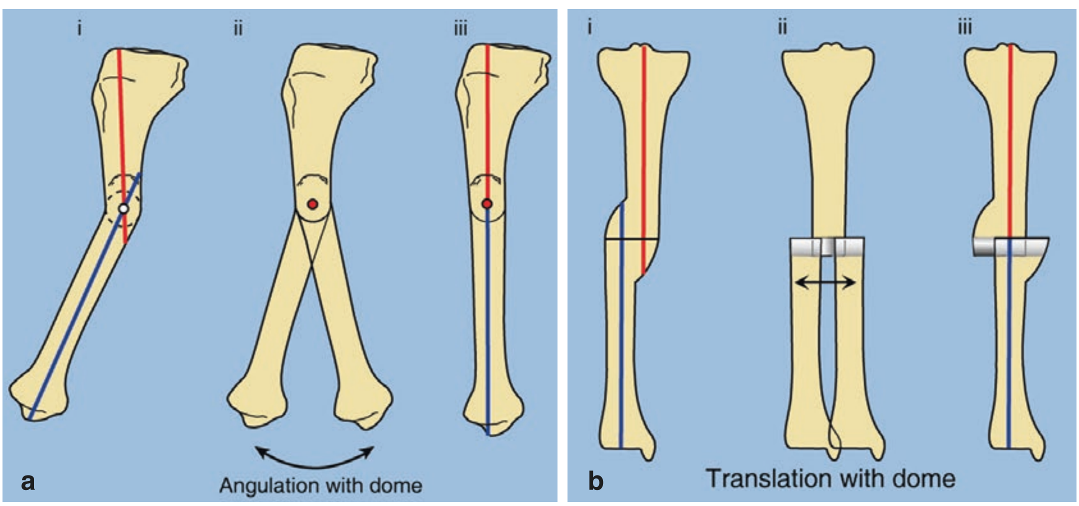

Fig. 8.5 (**a**) Focal dome osteotomy allows simultaneous correction of recurvatum and lateral translation of the tibia (i, ii, and iii). The dome osteotomy does not allow correction of axial rotation. (**b**) AP (i) and LAT (ii) view radiographs show lateral translation and recurvatum malunion deformities, respectively. There is also medial compartment osteoarthritis

8.7 Hardware

8.7.1 Plate Fixation

The plating technique depends on the type and level of the osteotomy performed. For opening wedge correction, the plate should be located on the concave or convex side. Biomechanically, the best location for a plate is on the side of the base of the opening wedge correction (Figs. 8.6 and 8.7).

The intact cortex acts as one intact column and the plate as the other. Axial loading places significant shear stresses on the screws. Bone grafting, if used, can be performed under the plate. The intact periosteum on the convex side should be preserved. If the plate is placed on the convex side, it is exposed to significant bending forces, and unless a solid graft is interposed into the opening wedge space to share the load, it will likely fail. If, instead of a graft, a step is incorporated into the plate, axial loading will pass from the bone through the plate because that becomes the path of least resistance. Therefore, the screws are protected by the step. Reduction before fixation can be facilitated by using an external fixator as a distractor. The distractor used can have a single fixation pin proximally and distally. This is unstable in the plane perpendicular to the fixator. Using an external fixator with two pins proximally and two distally provides better biplanar control during the correction. All four

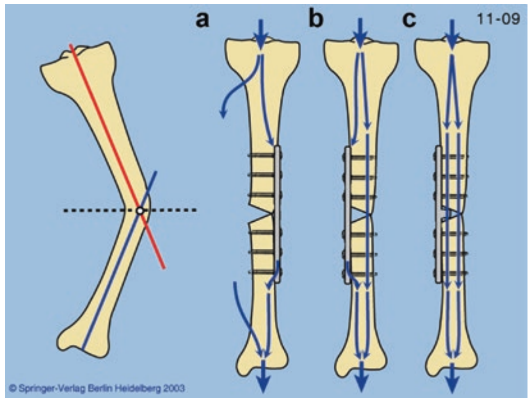

Fig. 8.6 (**a**) Varus deformity at the tibia diaphysis. (**b**) Osteotomy at the mid-diaphyseal section to have the convex hinge point. Opening wedge correction with a lateral plate. This plate may fail because of the large axial generated bending forces. (**c**) Same osteotomy as that shown in b, with the plate on the concave side. Axial forces exert high shear forces on the screws. (**d**) Step plate used to allow transmission of the axial forces in a direct line. The screws are protected from loading by the step in the plate

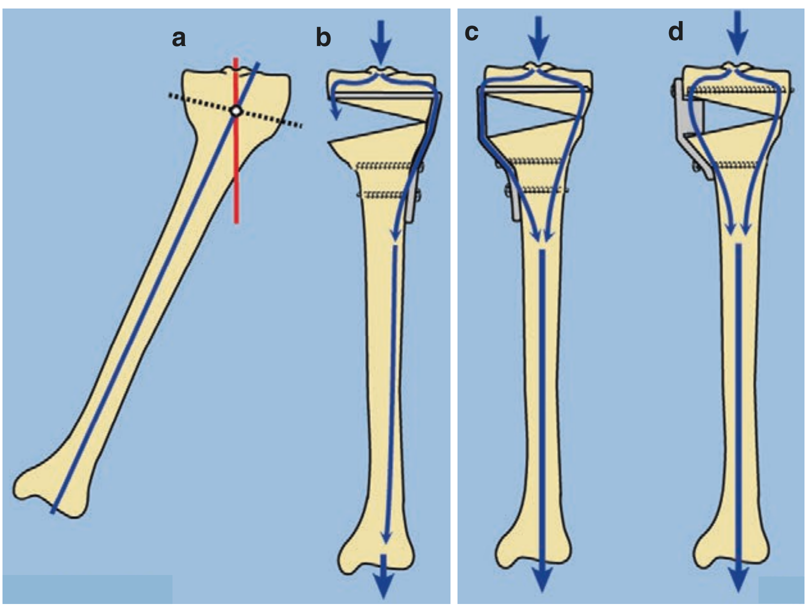

Fig. 8.7 (**a**) Varus deformity of the proximal tibia. (**b**) Osteotomy of the proximal tibia to have the convex hinge point on the tBL of the CORA. Opening wedge correction with a lateral plate. Because of the large bending forces, a blade plate is chosen. Even so, this plate may fail because of the large axial generated bending forces. (**c**) Same osteotomy as that shown in b, with the plate on the concave side. Axial forces exert high shear forces on the screws. (**d**) Step plate used to allow transmission of the axial forces in a direct line. The screws are protected from loading by the step in the plate

pins can be in the same plane, or two separate distractors, each with one pair of pins in planes that are perpendicular to each other, can be used. With only one pin above and one below in a single plane, there can be difficulty controlling or preventing deformity in the plane perpendicular to the pins. We call this technique *fixator-assisted plating*.

Deformities at the ends of bones (CORA in metaphysis or epiphysis) have limited space for fixation between the osteotomy level and the physis or joint. The farther the osteotomy level is away from the CORA, the more translation is required at the osteotomy site to avoid creating secondary deformities. Traditionally, plates have been the preferred hardware in metaphyseal regions. Some plate designs incorporate translation into the correction (e.g., hip varus osteotomy plate). Most other plates do not intentionally incorporate the translation into the plate; therefore, secondary deformities are created unless special care is taken to compensate. The plate for supracondylar osteotomy of the distal femur is an example of a plate design that attempts to incorporate translation. It usually produces a medial translation deformity when used for varus osteotomy of the distal femur (Fig. 8.8).

This plate is designed for fracture reduction and fixation and not for reconstructive osteotomies. In fracture treatment, the aim of treatment is restoration of the normal anatomy. Most plates are designed anatomically. Knowing this, one can modify the application of plates for use in juxta-articular deformity correction (e.g., using the 95° angled blade plate from the medial side for valgus to varus distal femoral osteotomy correction) (Fig. 8.8). Another alternative is to accept some secondary deformity in cases in which the amount of translation is small and of little clinical significance. If one does accept this, it is better to do so knowing that a mild secondary deformity of little consequence will arise rather than not recognizing this effect, which in larger deformities may be very clinically significant. Understanding the principles of deformity correction does not mean that every correction must be absolutely geometrically correct. It means that for every deformity correction, one should understand the geometric ramifications and assess them for their clinical significance.

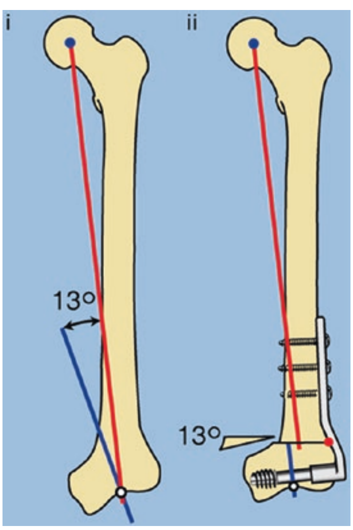

Fig. 8.8 The standard condylar screw plate for the distal femur will lead to medial translation deformity when a varus osteotomy is performed. It does not allow for necessary lateral translation at the osteotomy site

Special opening wedge plates that have steps of different widths incorporated into their walls can be used in the metaphyseal regions. To avoid secondary translation deformity, the hinge point of the opening wedge osteotomy is chosen to be as near as possible to the level of the CORA. The osteotomy is often inclined so that it can be started at a convenient level distant to the CORA but ended at the hinge point, which is at the CORA. Furthermore, the cortex near the CORA is left intact and can thus serve as a hinge axis. In metaphyseal regions, opening wedges smaller than 10 mm usually do not require bone grafting.

The typical plate has screws that are not physically linked to the plate. The plate and screw are connected only by friction from compression of the screw head onto the plate and bone. Another type of plate system has the screws attached to the plate. This converts the plate into an internal fixator. This system may become more popular in the future. It may prove useful for stabilizing opening wedge osteotomies and limb lengthening distraction gaps. Its increased stability may also make it more useful in the treatment of nonunions and diaphyseal osteotomies. When the screws are connected to the plate, the system acts like an implantable external fixator (Fig. 8.9).

Because of the less invasive nature and the superior fixation afforded by nails in diaphyseal regions, there is little indication for the use of plates in diaphyseal deformities of the femur and tibia. Exceptions to this are cases in which it is techni-

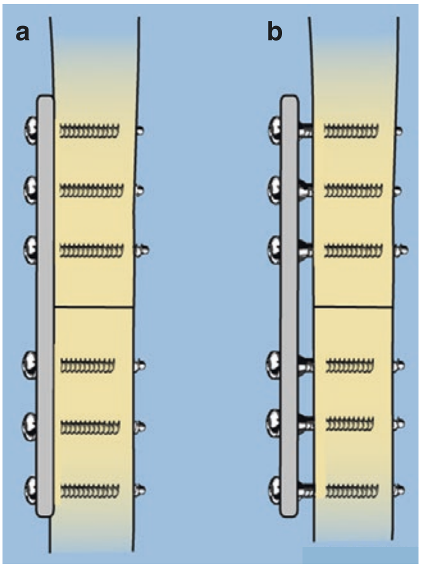

Fig. 8.9 (**a**, **b**) Internal fixation with plates relies on friction between the screws, plate, and bone from the compression generated by the screws (*left*). The internal fixator is a plate with connected screws (*right*). This type of plate functions like an external fixator in which the cantilever forces on the screws are minimized

cally too difficult or risky to insert a nail (e.g., sclerotic medullary canal, discontinuity of the canal due to translation deformities, open physis). Active or latent infection is usually a contraindication to both plating and nailing. Previous infection is not necessarily a contraindication to plating or nailing if the infection is thought to have been successfully eradicated by previous treatment.

Plating requires more surgical exposure than do other methods. Current techniques using indirect traction with a distractor minimize the exposure needed. The accuracy of plating in metaphyseal regions varies greatly with different operators. Even very skilled surgeons have an accuracy of only approximately 5°. This accuracy can be further improved if the MAT is used intraoperatively (intraoperative radiograph) after temporary or limited fixation is achieved. The osteotomy can still be adjusted after the MAT. The final fixation is applied only after the desired joint orientation is achieved.

8.7.2 Intramedullary Nailing (IMN)

IMN offers the advantages of a limited open procedure, remote insertion site, and percutaneous osteotomy. The hardware is buried and well tolerated for lengthy periods of time. Even removal does not require extensive surgical exposure. Diaphyseal angular deformities, especially around the isthmus, are easily realigned using IMN. The isthmus of the bone directs the nail path so that a diaphyseal angular deformity automatically realigns as the nail passes. For more proximal or distal diaphyseal deformities and for metaphyseal deformities, the path of the nail is not as constrained, and the nail may deviate from the center of the bone once it crosses the osteotomy site. Therefore, it is essential to choose the correct starting and ending points. It is not sufficient to obtain just one of these two points correctly (Figs. 8.10 and 8.11).

Accuracy can be improved using the FAN technique (Figs. 8.12) [10, 12]. The accuracy comes from the adjustability of the external fixator and the check radiograph(s) that is obtained before inserting the definitive internal fixation.

Correction of length with or without deformity correction can also be achieved using IMN fixation by the lengthening over nail (LON) technique (Fig. 8.13) [4, 5, 10].

Limb lengthening techniques will be explained particularly in related chapters of this book.

8.7.3 External Fixation

External fixators can be used at any level in a bone. They offer excellent fixation for juxta-articular regions. Circular fixators using tensioned wires require the least amount of bone length for fixation of any of the hardware methods. External fixators can be used with gradual or acute deformity correction. Gradual deformity correction is especially useful for large deformities or when there is a neurovascular or other soft tissue structure at risk (SAR) from acute correction. Bone at risk of poor healing (congenital pseudarthrosis of the tibia, rickets, adult diaphyseal bone) should usually be corrected gradually to minimize injury to the periosteum. Acute correction can be used in deformities of lesser magnitude, especially in the metaphyseal regions of the tibia or both metaphyseal and diaphyseal regions of the femur. There is a greater risk of bone healing problems with acute corrections, especially in

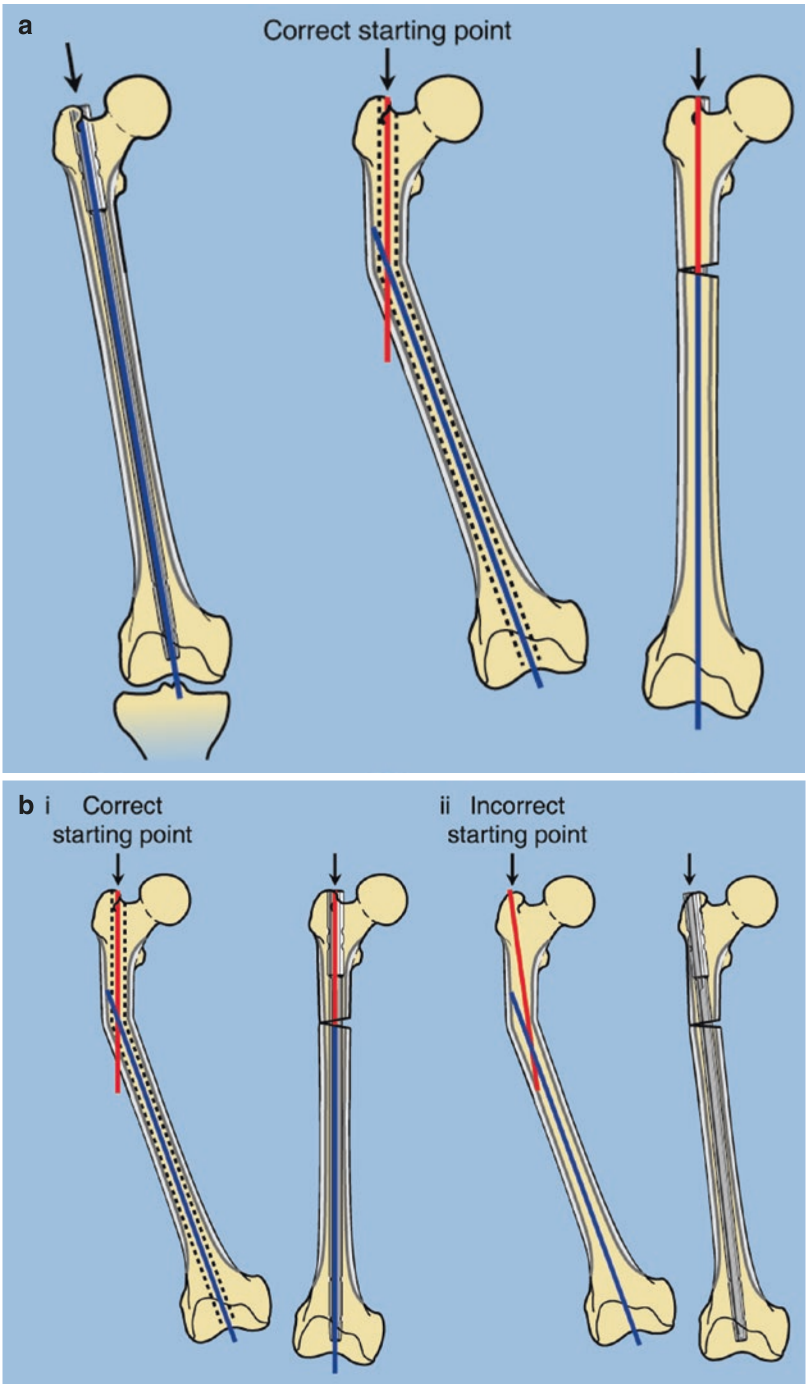

Fig. 8.10 (**a**) An IMN follows the medullary canal and, therefore, the anatomic axis of the femur. The correct starting point for the proximal femur is the piriformis fossa. The correct ending point should be at the center of the femoral condyles, with the nail pointing toward the medial tibial spine. (**b**) With correct starting and ending points, an IMN can be used to fully correct a femoral deformity (**i**). If the starting point is too lateral, such as in the greater trochanter, the varus will be only partially corrected despite the correct ending point (**ii**). (**c**) Similarly, for infra-isthmic deformities, not only is the correct starting point important but also the correct ending point (**i**). Insufficient correction with excessive varus or valgus is associated with a noncentralized ending point (**ii**)

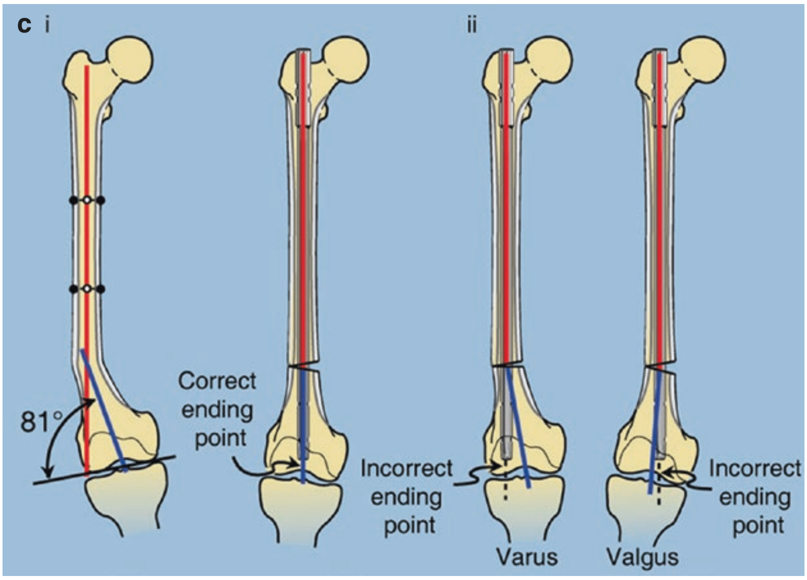

Fig. 8.10 (continued)

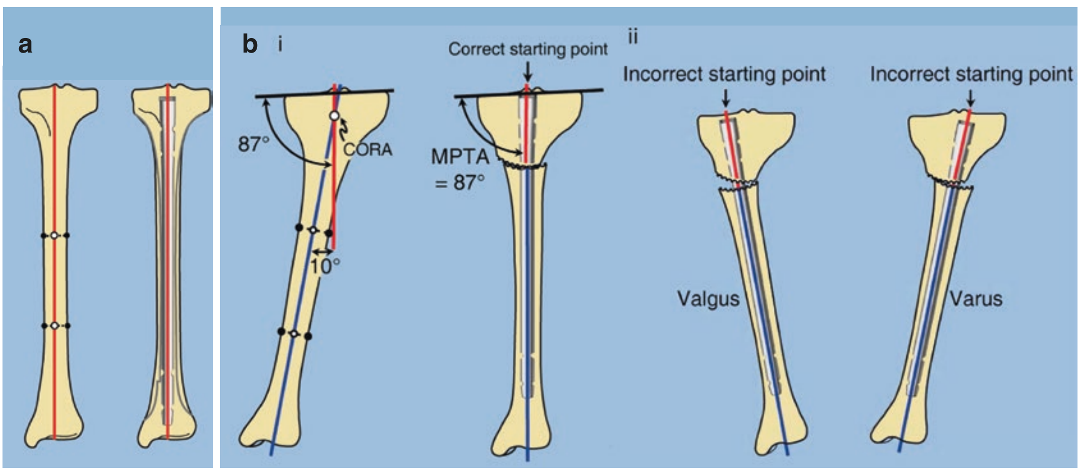

Fig. 8.11 (**a**) In the non-deformed tibia, the mid-diaphyseal line usually passes through the medial tibial spine. Therefore, the correct starting point is at the medial tibial spine. In some non-deformed tibiae, the mid-diaphyseal line passes more laterally. It is important to know this before starting the nailing. (**b**) With a focal dome osteotomy, the starting point must be correct (**i**). If the nail starting point is too lateral, a varus deformity will result, whereas if it is too medial, a valgus deformity will occur (**ii**)

adults. Acute correction is also more likely to cause stretch injury to neurovascular structures and lead to increased compartment pressure. External fixation osteotomies can often be performed with minimal invasiveness using percutaneous techniques, usually of the opening wedge type, with or without translation.

Angular deformity correction with circular external fixation uses hinges. The imaginary line passing through the axis of rotation of two collinear circular fixation hinges is the ACA. If the axis of the hinges is matched to the level of a CORA on the bisector line and is perpendicular to the plane of angulation, the proximal and distal

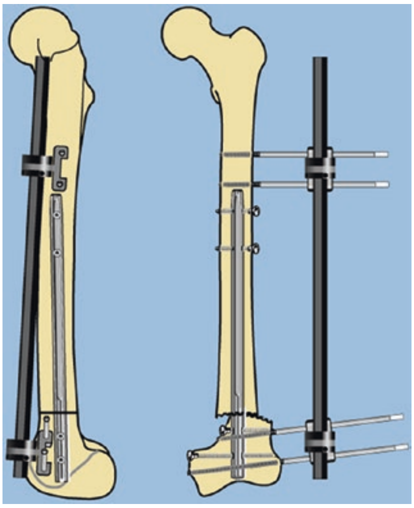

Fig. 8.12 Illustration of FAN technique after osteotomy with the implant and fixator applied. The nail is inserted and locked proximally and distally. The distal screws are easier to insert from the medial side to avoid collision between the locking guide and the fixator. The fixator body is anterior to the femur so that it does not obstruct visualization of the femur by the image intensifier

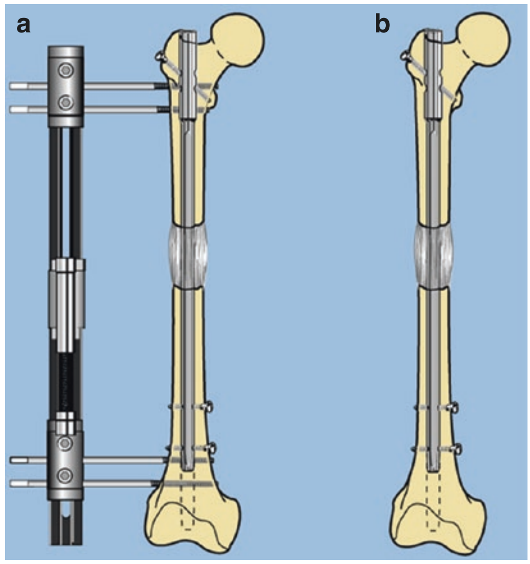

Fig. 8.13 (**a**, **b**) Illustration of the LON technique. The nail must be locked from the medial side to avoid contamination from the half-pin sites. The fixator can then be removed. The nail maintains the length of the femur while the regenerate bone consolidates

axis lines will realign with correction of angulation around the hinges. If the osteotomy is at the level of the CORA, the hinge correction will follow osteotomy rule 1. If the osteotomy is at a level different from that of the hinge, correction will follow osteotomy rule 2.

The circular fixator can be constructed before surgery to the diameter, length, and deformity parameters of the limb. After measuring the patient for the correct ring diameter (large enough to allow for two finger's breadth circumferentially around the limb segment) (Fig. 8.14), the rest of the preconstruction is based on the preoperative planning from two orthogonal radiographs.

The levels of all the rings are marked on the radiographs. In general, the full length of the bone is used for fixation. In the tibia, the proximal-most ring is usually placed at the level of the flare of the bone (Fig. 8.15). The distal-most ring is placed within 1 or 2 cm of the plafond. In the femur, the distal-most ring is at the level of the adductor tuberosity. In the proximal femur, it is at the level of the lesser trochanter (Fig. 8.16).

The other general rule is that the distance between the pair of rings on opposite sides of the hinges is one hand's breadth (10 cm). The reason for this is to maximize the leverage of the device. The limiting factor for bending strength is the diameter of the threaded rods (usually 6 mm) (Fig. 8.17).

Therefore, keeping the distance between the rings that hold the hinges to 10 cm maximizes the bending strength of the device (Fig. 8.15). The other rings are spread out maximally in the bone to maximize the lever arms of fixation on either side of the osteotomy. The two hinges are made collinear with each other by first making sure that they are at the same level and that they are oriented the same way. To do this, bend the hinges to 90° and tighten the connections of the threaded rods to the proximal and distal rings. It is very important to place the hinges in the correct orientation to the plane of angulation. For example, for a frontal plane angulation, the hinges should be oriented anteroposterior (perpendicular to the plane of angulation). Because the correction is almost always an opening wedge correction, the hinges are located one hole convex to the central bolts that connect the two half

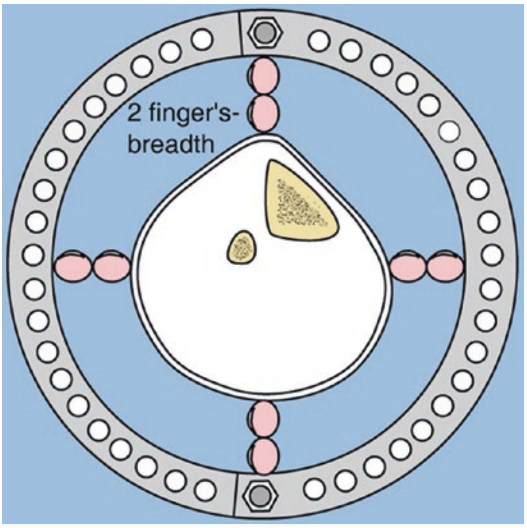

Fig. 8.14 For circular external fixators, such as the Ilizarov device, the ring size chosen should allow approximately two finger's breadth of space between the ring and the widest part of the limb segment

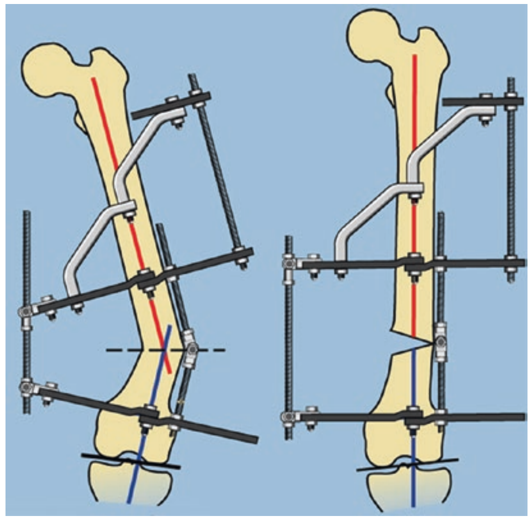

Fig. 8.16 Femoral apparatus for varus deformity. The upper femoral arch is at the level of the lesser trochanter, and the lower femoral ring is at the level of the adductor tuberosity. The space between the rings on either side of the CORA is one hand's breadth

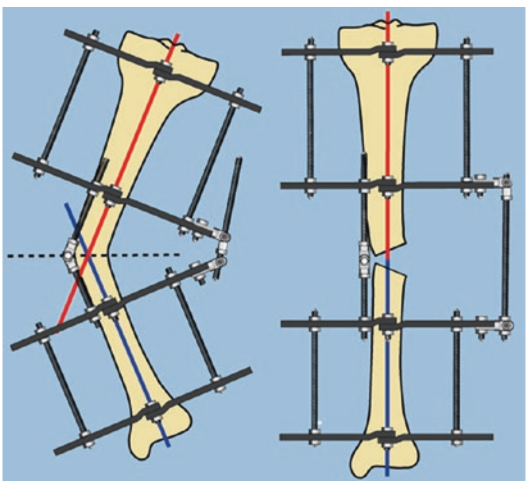

Fig. 8.15 Four-ring apparatus with middle rings one hand's breadth apart. The rods do not bend, and full correction is easily achieved because of sufficient leverage on both sides of the osteotomy. The upper tibial ring is at the level of the flare of the tibia, and the lower tibial ring is 1–2 cm proximal to the ankle joint

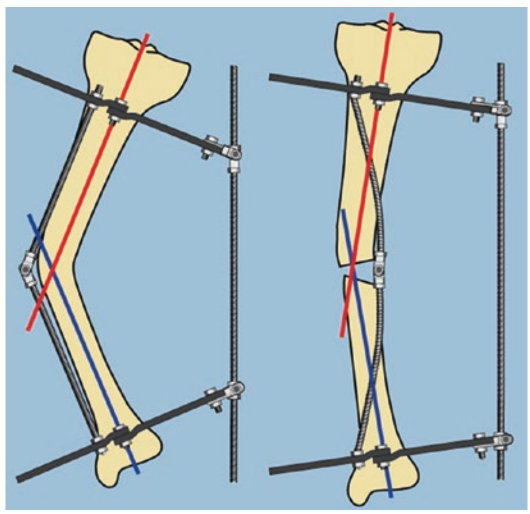

Fig. 8.17 Two-ring apparatus with rings far apart. If the entire fixation is at these two levels, the leverage on the bone is limited. The 6-mm threaded rods will likely bend while the apparatus is trying to straighten the bone. Incomplete angular correction may result

rings together. The two central bolts represent the sagittal plane. On our oblique plane analysis graph, these bolts also represent the *y*-axis. To center the apparatus accurately on the limb, we rotate the limb until the patella is forward. We then orient the two central bolts anteroposteriorly and, if possible, confirm by using the image intensifier that they overlap. We then fix the apparatus to a reference wire that is in the frontal plane. The next step is to make sure that the hinge is at the level of the CORA. This can be accomplished by measuring the level of the CORA relative to the knee on the radiograph and reproducing this measurement using the image intensifier intraoperatively after compensating for magnification. The hinge level is adjusted to the level of the CORA, and a distal reference wire is then inserted to fix the distal part of the apparatus. If the hinge level is not correctly adjusted to the level of the CORA and the osteotomy is made at the CORA, the bone osteotomy will translate. It is important to ensure that the hinges are at the correct level along the longitudinal axis, and it is important to make sure that the hinge is located correctly on the bisector line. If the hinge location is at the lateral cortex, an opening wedge correction will occur. If the hinge is located at the concave cortex, the bone ends will be compressed together, unless a wedge is resected, because the net effect is a closing wedge osteotomy. The apparatus should be correctly oriented and fixed on the limb with the ACA of the hinges perpendicular to the plane of deformity and at the correct level of the CORA, usually on the opening wedge side of the bone. If the apparatus is being used for an oblique plane correction, the only difference is the location of the hinges on the ring. To find the correct location, we use the graphic method of oblique plane planning to locate the correct holes for the hinges. The centering of the apparatus is performed in the same way as for a frontal plane deformity. After the apparatus is in place with two pins (wires or half pins), the rest of the pins are placed to achieve stable fixation. The pattern of safe wire and half-pin fixation was illustrated for the femur and the tibia on previous chapters. If only wires are used for fixation, it is important to incorporate olive wires in strategic locations. This follows the "rule of thumbs" as mentioned in previous chapters. For juxta-articular angular deformities, a juxta-articular hinge is used instead (Fig. 8.18).

The rate of correction for angular deformities must follow the biological principles of rate and rhythm of bone regeneration. Therefore, it is important to calculate the rate of correction according to simple mathematical rules [7, 9]. The duration of correction can also be calculated [6]. To calculate the duration of correction, one needs to know the rate of correction of the bone. Because the bone is opening as a wedge shape in a circular direction, the duration of correction will be the length of the arc divided by the rate of correction along that arc. The length of the arc is the fraction of the circumference of the circle at the radius of the bone edge from the hinge (r) and of magnitude a (2pra/360). If the rate of correction is set to 1 mm per day, the duration of correction is 2pra/360 days (where r is measured in millimeters). If one is performing lengthening and deformity correction simultaneously, to calculate the rate of distraction at the distraction rod, we need to know the overall rate of lengthening and the ratio of deformity correction based on the rule of triangles or concentric circles described above. For example, if the rate of lengthening is 0.5 mm per day, this leaves 0.5 mm of distraction of the bone available (assuming we do not want to distract the bone faster than 1 mm per day at any point on the osteotomy line). If the rate ratio of the distraction rod to the hinge versus the bone edge to the hinge is 4:1, we want to calculate how many millimeters per day we can lengthen at the distraction rod to produce 0.5 mm of distraction of the osteotomy bone ends. This will be 4 ¥ 0.5 mm per day, or 2 mm per day. Because the overall lengthening rate is 0.5 mm per day of all the rods, the rate for the distraction rod is 0.5+2 = 2.5 mm per day. The hinge rods will be lengthened only 0.5 mm per day.

Rotation and translation can also be corrected acutely or gradually with various mechanisms and modifications of the apparatus (Fig. 8.19).

For rotation correction with circular frames, one must consider that because the apparatus is usually centered on the limb, it is not usually centered on the bone. Therefore, if rotation correction is performed around the center of the ring, the off-center bone ends will translate relative to each other. Because translation may be a product of gradual rotation correction, it is preferable to correct translation deformity last. The amount of translation deformity that will occur from rotation can be calculated. To avoid secondary translation deformity, the ring-within-a-ring construct can be used (Fig. 8.19).

When combinations of lengthening and gradual deformity correction are planned, the order of correction is important. It is preferable to correct length and angular deformity together and then rotation and translation. Both rotation and translation produce shear on the newly regenerated bone. This shear can be distributed over the entire length of the regenerate bone if rotation and translation are performed last.

Readers can find more information about advanced deformity correction techniques with monolateral fixators and recently developed non-circular external fixators in *Principles of Deformity Correction* from Springer.

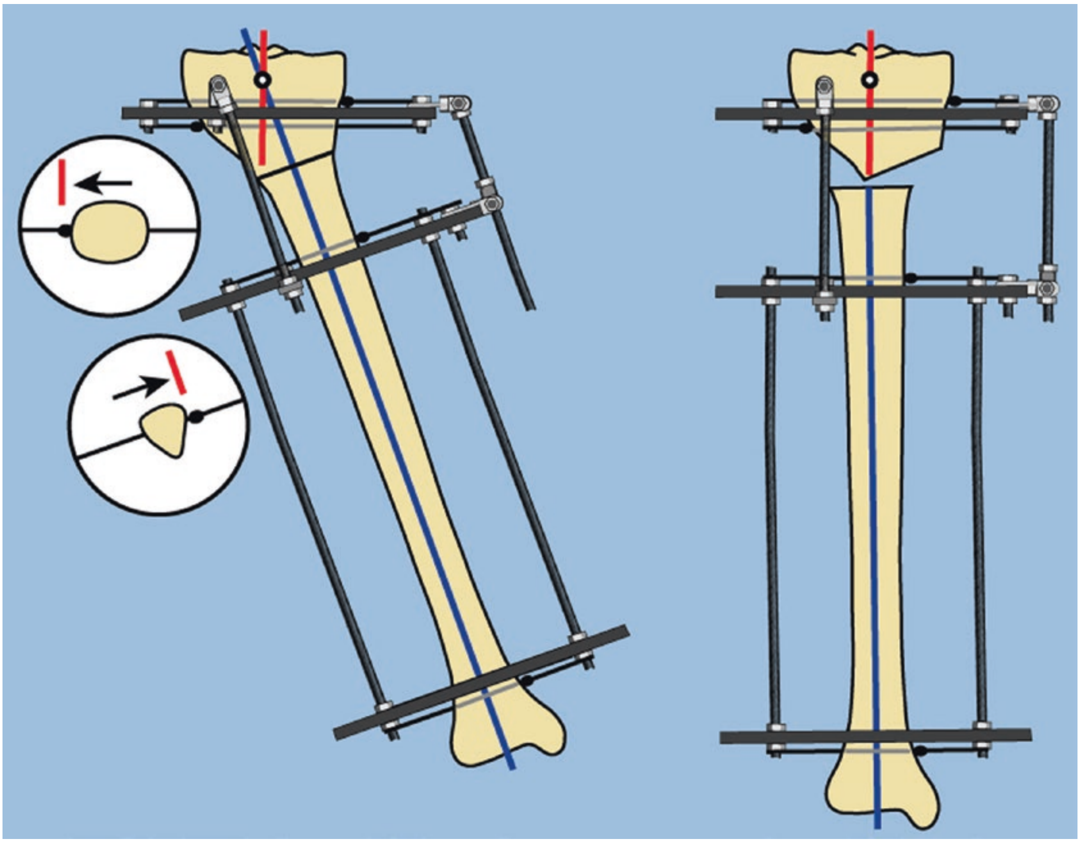

Fig. 8.18 (**a**) Varus deformity of the tibia with the CORA near the joint line. To match the hinge of the fixator to the level of the CORA, the hinge must be above the level of the ring. The hinge is therefore constructed in the manner shown. This is called a juxta-articular hinge assembly. To affect the translation with an all-wire frame, counter-opposed olive wires are required, as shown in the insets. If half pins are used, they constrain the bone, and olive wires are not required. (**b**) After correction, the axis lines are realigned. The osteotomy site bone ends are translated to each other according to osteotomy rule 2

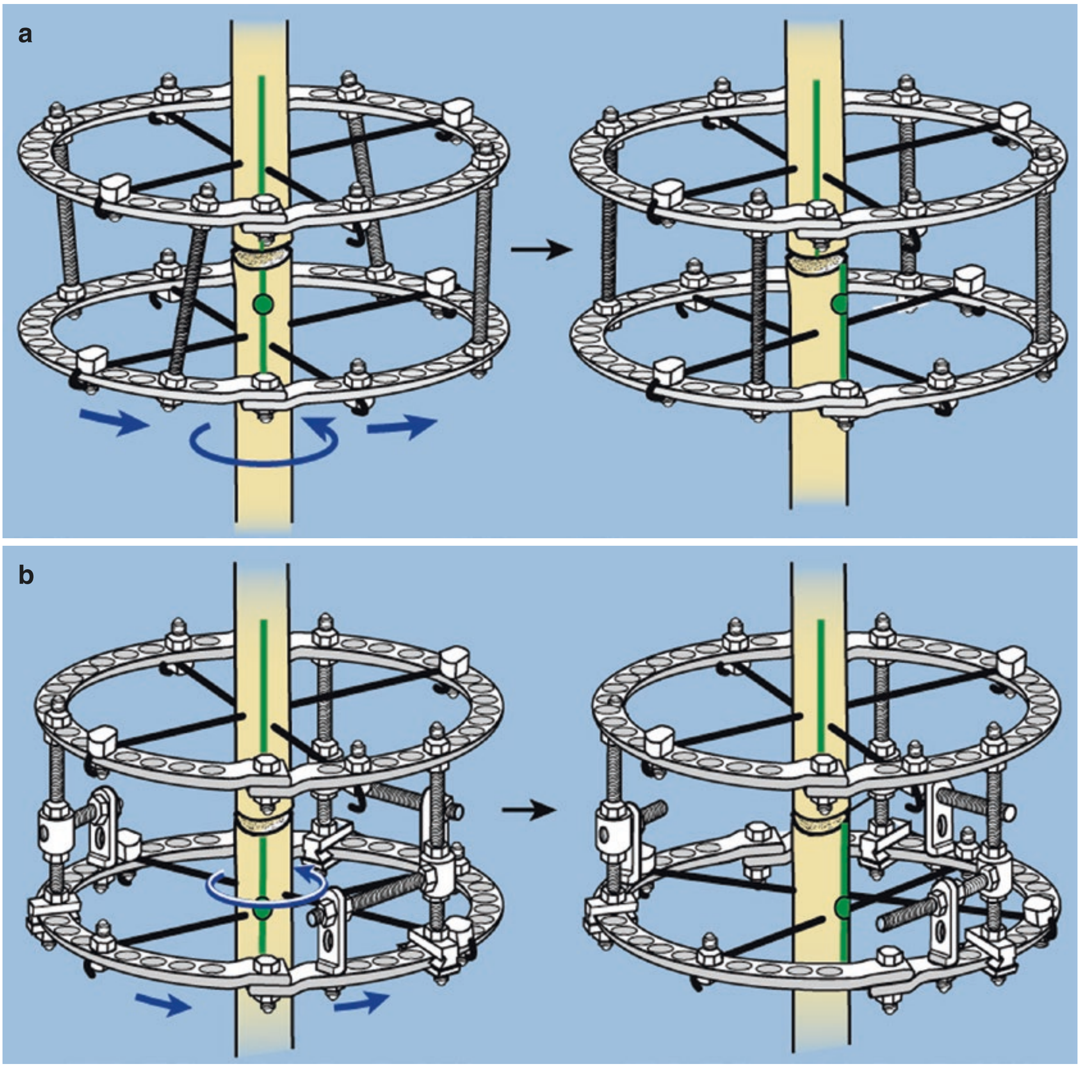

Fig. 8.19 (**a**) Acute rotation using offset threaded rods. This construct is good for one- or two-hole rotation corrections. It is fast to assemble and to use. (**b**) Gradual rotation correction using original Ilizarov parts. The transverse threaded rods are tangential to the ring. (**c**) Gradual rotation correction using Paley's rotation-translation boxes. The translation boxes are tangential to the ring. (**d**) Gradual rotation correction using the ring-within-a-ring construct. This construct is the only one that centers the rotation around the center of the bone instead of the center of the ring. One ring is connected to the upper block of rings, and the other is connected to the lower block of rings. Only one transverse rod is required. Parallel plates sandwich the ring-within-a-ring construct. This construct is difficult and time consuming to assemble

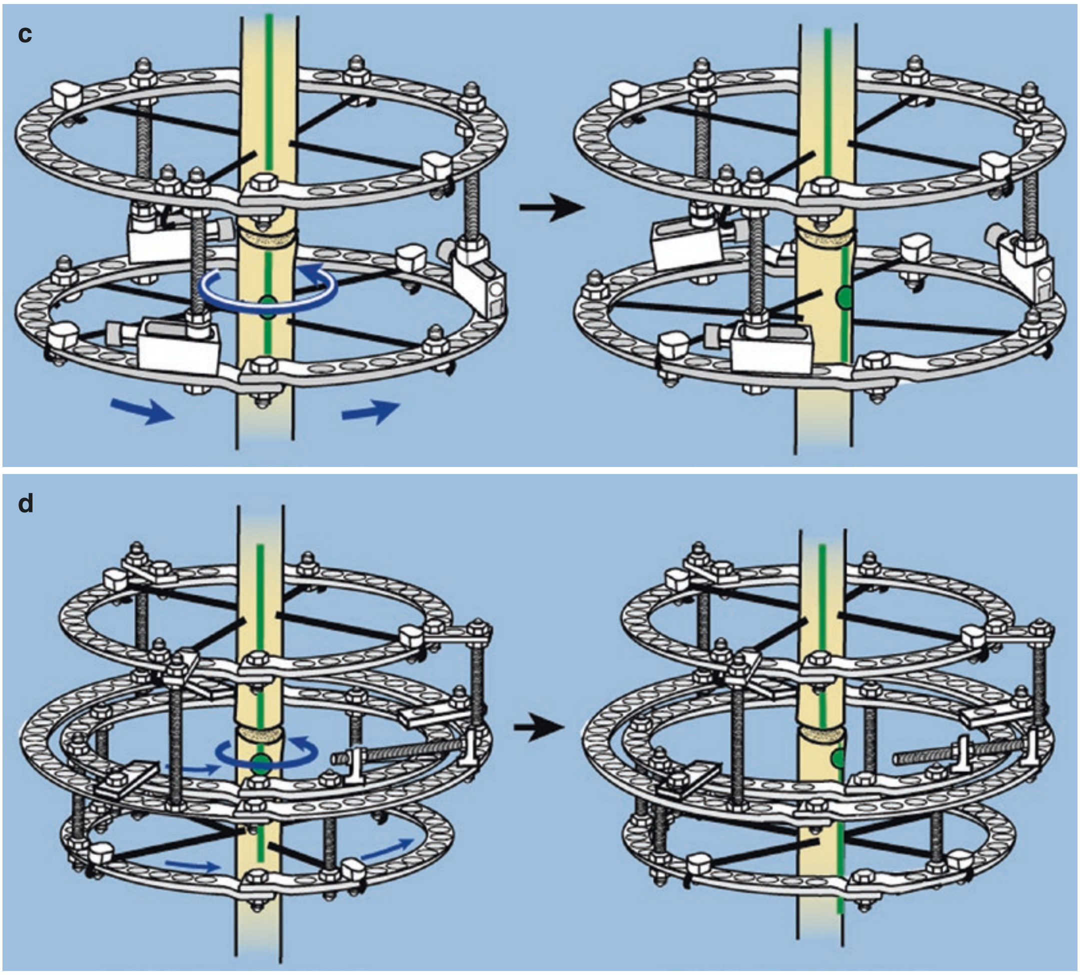

Fig. 8.19 (continued)

8.8 Order of Correction

With acute correction, it is preferable to correct rotation first, because rotation of an undisplaced bone usually maintains alignment and does not lead to displacement of the bone ends. In cases in which the bone ends were already translated, there is a strong likelihood for the ends to slip off each other, leading to marked instability. Acute angular correction leads to asymmetric tension in the soft tissues. This locks the bone ends together, preventing translation. Therefore, translation should always precede angulation for acute correction. One technical trick to translate the bone ends in the face of soft tissue tension is to insert an osteotome between the bone ends and twist it so as to separate the bone ends (disimpaction) and "walk" one end relative to the other.

The order for gradual correction of deformities starts with angulation and length together. If angulation is corrected alone and lengthening is then performed, there is a high risk that the convex cortex will prematurely consolidate before lengthening is performed. Because rotation correction is often performed around an axis that does not perfectly correspond to the central axis of the bone, unwanted secondary translation may arise. Therefore, translation is corrected after rotation.

The order of correction of deformities with acute correction is rotation before translation or angulation and then translation before angulation. The order of correction of deformities with gradual correction is angulation and length together, then rotation, and then translation.

Simultaneous six-axis correction using external fixation is the latest concept. This theoretically allows simultaneous correction of length, rotation, angulation, and translation. Practically, even with such devices, correction of translation cannot be achieved until the bone ends are out to length and clear of each other. This is further discussed in subsequent chapters.

8.9 Lever Arm Principle

Perhaps the most common mistake made with any form of fixation is not achieving stability. The length of bone fixed on either side of an osteotomy is critical to stability. Therefore, the lever arms should be considered. The lever arms are the lengths of the bone segments on either side of the osteotomies. If the joint at the end of a lever arm is stiff or fused, the lever arm extends to the next mobile joint. The femur in the case of proximal tibial osteotomies and the tibia in the case of distal femoral osteotomies can be counted as part of the frontal plane lever arm. In the sagittal plane, because the knee moves freely, the adjacent bone is not part of the lever arm. Ideally, it is desirable to have equal lengths of fixation on both sides of the osteotomy. This is possible only in middiaphyseal osteotomies. For metaphyseal osteotomies, the length of fixation on one side of the osteotomy is limited. Therefore, the type and amount of fixation is increased to balance the lever arms. Auxiliary devices such as orthoses and splints can be used to help balance the lever arms (e.g., knee brace or cast brace in conjunction with plate or IMN). An osteotomy near the knee, for example, experiences very low lever arm forces in the sagittal plane as long as the knee is mobile. Lever arm forces will act through the path of least resistance, which in the sagittal plane is the knee throughout the range of knee motion. At the extremes of motion, the osteotomy will experience lever arm forces. Therefore, HE forces and exercises should be avoided and neutralized with an extension stop to a brace. In the frontal plane, the path of least resistance is not the knee because there is no knee range of motion in the frontal plane. The path of least resistance, therefore, may be the internally fixed osteotomy site, and a long leg brace may be useful to neutralize the frontal plane lever arm forces. It is not necessary to lock the brace for flexion except to prevent HE forces. When there is a stiff joint adjacent to an osteotomy, the lever arm on the stiff joint side is very long. Neutralization of the lever arm may be required to prevent nonunion or hardware failure. Neutralization can be achieved either by external bracing or external fixation across the stiff joint. Rarely, neutralization is achieved by extending internal fixation temporarily across a joint.

8.10 Method of Osteotomy

Although osteotomy types will be discussed in subsequent chapters, it is important to emphasize that all osteotomies that are performed via extensile exposure cause some devascularization of the bone. Dissection of the periosteum should be minimized to limit damage to this fragile tissue. Power instruments can cause thermal necrosis of bone. To prevent this, the saw blade should be irrigated with cold saline during the bone-cutting process. A start-stop technique is also important to prevent thermal injury.

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